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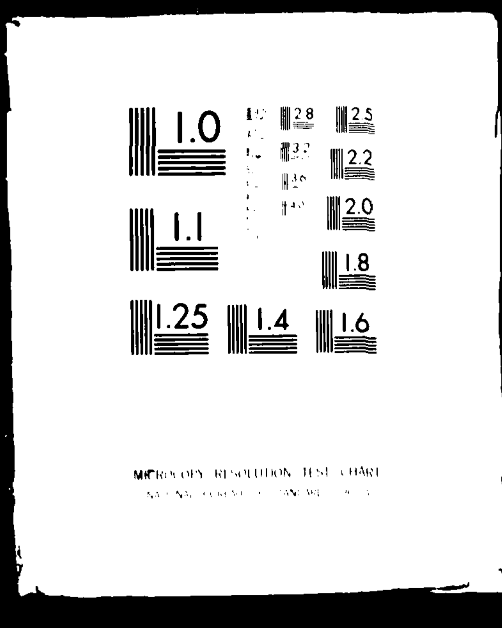

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LEVEL III

TACTICAL RADAR TECHNOLOGY STUDY

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GCI - Ground Control Intercept
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Mobile Tactical Radar
Solid State Transmitter
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Distributed Microprocessor Radar Controller

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report presents results of a study to identify new technology required to provide advanced multi-threat performance capabilities in future tactical surveillance radar designs. A baseline design with optional subsystem characteristics has been synthesized to provide both functional and operational survivability in a dynamic and hostile situation postulated for the post-1985 time frame. Comparisons have been made of available technology with that required by the new baseline (Cont'd)

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design to identify new technology requirements. Recommendations are presented for critical new technology programs including estimates of technical risks, costs and required development time.

PREFACE

This report describes work performed by ITT Gilfillan for Rome Air Development Center (RADC) under Contract No. F30602-79-C-0026. The Project Engineer for RADC was Mr. Thomas B. Shields.

The objective of this study was to identify new technology required to provide advanced multithreat performance capabilities in future tactical surveillance radar designs. This report summarizes the results of steps leading to the identification of new technology: an analysis of current threats and those expected in the 1990s; a determination of the functions, operations and mission of the TACS and its sensors, and the environment in which they operate; then formulating a baseline advanced tactical radar against which current and future technology can be evaluated. The baseline ATR system synthesized in this study meets the mission and threat requirements of the post-1985 era. This multiple function radar combines a unique antenna/transmitter with advanced signal processing techniques to automatically track and report targets in a heavy ECM environment.

The report was edited by the Principal Investigator, Mr. Ronald Rosien. The system description and performance predictions found in Sections 3 and 8 were accomplished by Mr. Leo Cardone. Mr. Joseph Petersam contributed the threat analysis and requirements determination of Section 2. Signal Processing efforts were directed by Dr. David Hammers with the Waveform Development (Section 4) contributed by Mr. Albert Klein, and Automatic Tracking by Mr. Edward Nozawa. The functional technology areas in Section 6 were written by: Dr. George Hockham (Antenna), Mr. Harvey Hom (Solid State Transmitter), Mr. Stanley Goldman (Tube Transmitter), Mr. Willis Blackstone (Receiver), Mr. Charles Lucas (Processors), Mr. Reese Briggs (Mechanical).

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Section 1

INTRODUCTION AND SUMMARY

1. INTRODUCTION AND SUMMARY

1.1 STATEMENT OF THE PROBLEM

Current TACS ground radars cannot satisfy future TACS requirements based on projected threat environments. Consequently, the "Tactical Radar Technology Study" and other related studies are being directed to support the Air Force program to develop a tactical surveillance radar for the post-1985 time frame which will ensure both functional and operational survivability in the projected dynamic, hostile situation.

Current and projected mobility of ground forces and fluid tactical situations demand that emphasis be placed on very high mobility for all elements of the future TACS. It is unlikely that setup and teardown times exceeding 15 minutes will be tolerable for those TACS elements, especially the Advanced Tactical Radars (ATR) that will be deployed near the FEBA.

The future EW environment postulates active enemy ECM directed against TACS radars and communications/data links. Chaff will be deployed to disable radars without sophisticated signal processing and also combined with other ECM resources, to degrade radars utilizing advanced signal processing techniques. Direct physical attack on some or all friendly radiators (sensors and communications) is to be expected from cruise missiles, ARMs and RPVs.

The present TACS radars will not be able to provide surveillance coverage beyond the FEBA when subjected to the postulated hostile ECM. Coverage of sectors or corridors on both sides of the FEBA will be denied by enemy jamming and chaff. Although an upgraded AN/TPS-43E radar, outfitted with the ultra-low sidelobe antenna (ULSA), should improve surveillance somewhat and keep denied sectors to a minimum, it is most probable that full coverage in such sectors can only be provided by introducing new surveillance concepts that enhance TACS functional and operational survivability.

The synthesized baseline ATR design, detailed in this report, is based on a new surveillance system concept. This concept utilizes a sensor net of new ground based long range radars (ATRs) augmented by the Army Air Defense radars and further augmented by new ground-based gap filler radars and the E-3A as a means for obtaining low level coverage. For logistics effectivity, the new gap filler radar is envisioned as a lower module variant of the long range ATR. As such, both radars must have good ECCM and Anti-ARM capability. They must provide automatic track initiation and maintenance, and be able to store and exchange track information with neighboring radars as well as to report all tracks to operations centers.

The operations centers will be the primary command and control elements of the TACS and may or may not have radars colocated with them. However, residual control capability will exist at each radar site as a backup capability in the event that one or more operations centers are lost. Therefore, each radar site must be able to communicate with

aircraft and be capable of performing the functions of identification, GCI, air traffic control, etc. The number of radars (both long range and gap fillers) associated with each operations center, as well as the number of operation centers, will vary with the specific theater requirements. It is assumed in this concept that all of the TACS operations centers will be netted with each other as well as with the E-3A and the Army TSQ-73.

Certain required ATR performance characteristics can be deduced from the future TACS operational/configurational requirements. For example, emphasis must be placed on the development of highly jam-resistant short-to-medium range ATRs featuring waveform generation/processing flexibility to obtain long-range surveillance/identification data when possible. Also, the ATR design must utilize wide dynamic range, coherent transmissions and adaptive signal processing to effectively discriminate against clutter, chaff and weather. Another required characteristic is rapid ATR setup and teardown, on the order of 15 minutes or less, to ensure operational survivability.

1.2 STUDY METHODOLOGY

The methodology employed in conducting the "Tactical Radar Technology Study" was a top down process beginning with a mission analysis of the future TACS, a requirements definition for the ATR and establishment of a candidate baseline ATR design approach that could satisfy all requirements. The process then involved tradeoffs between requirements, alternative concepts/implementations, and cost. The study output was the identification of required technology advances and future tradeoff studies.

The Radar Technology Study was performed in accordance with the task flow network of Figure A. Essential study tasks were: 1) to formulate a baseline ATR design concept based on satisfying the functional requirements for air surveillance/identification and meeting the operational requirements for mobility, air transportability, etc., and 2) to compare available technology with that required by the baseline ATR design in order to identify where new technology advances are required. The baseline ATR design, synthesized in Section 3 of the report, is summarized in the following section, and the technology advances required, summarized in Section 1.4, are identified and documented throughout the report.

The formal study was initiated by performing the requirements analysis task which necessitated a familiarization with the functions, operations and missions of the TACS in scenario and under present and future threats. The task was executed in general through a literature search and in particular through assimilation of information contained in the following Air Force Reports: "Project Seek Screen" RADC TR-75-320, "Tactical Air Forces Integrated Information System (TAFIIS) Master Plan" TAFIG-78-1, and "Tactical Air Control System; Alternative Surveillance System Concepts Study" RADC-TR-79-136. Completion of the requirements analysis task resulted in the quantification of the operational/configurational requirements for future TACS elements and permitted formulation of the ATR's design requirements based on the threat and the TACS requirements. The results of the Radar Design Requirements study task are detailed in Section 2 and Appendix A of this report.

Although three candidate ATR designs were initially postulated to obtain alternative levels of performance with attendant alternative levels of acquisition cost for relative evaluation, it was eventually decided to select/definitize and evaluate one configuration, a mid-level performance/mid-level cost candidate. This decision was prompted by the need for expediency, considering the short term of the study, and by the recognition that economic considerations will and must play a large part in determining the ATR configuration eventually selected for development/deployment. In this regard, the baseline design approach proposed for evaluation can not be a constrained design, conversely, it must be capable of providing either greater or lesser performance without requiring adoption of an entirely new design approach. Since this is the case for the baseline design selected it provides the needed reference to identify required new technology advances and to perform future cost-vs-performance tradeoffs that are essential in determining the optimum ATR.

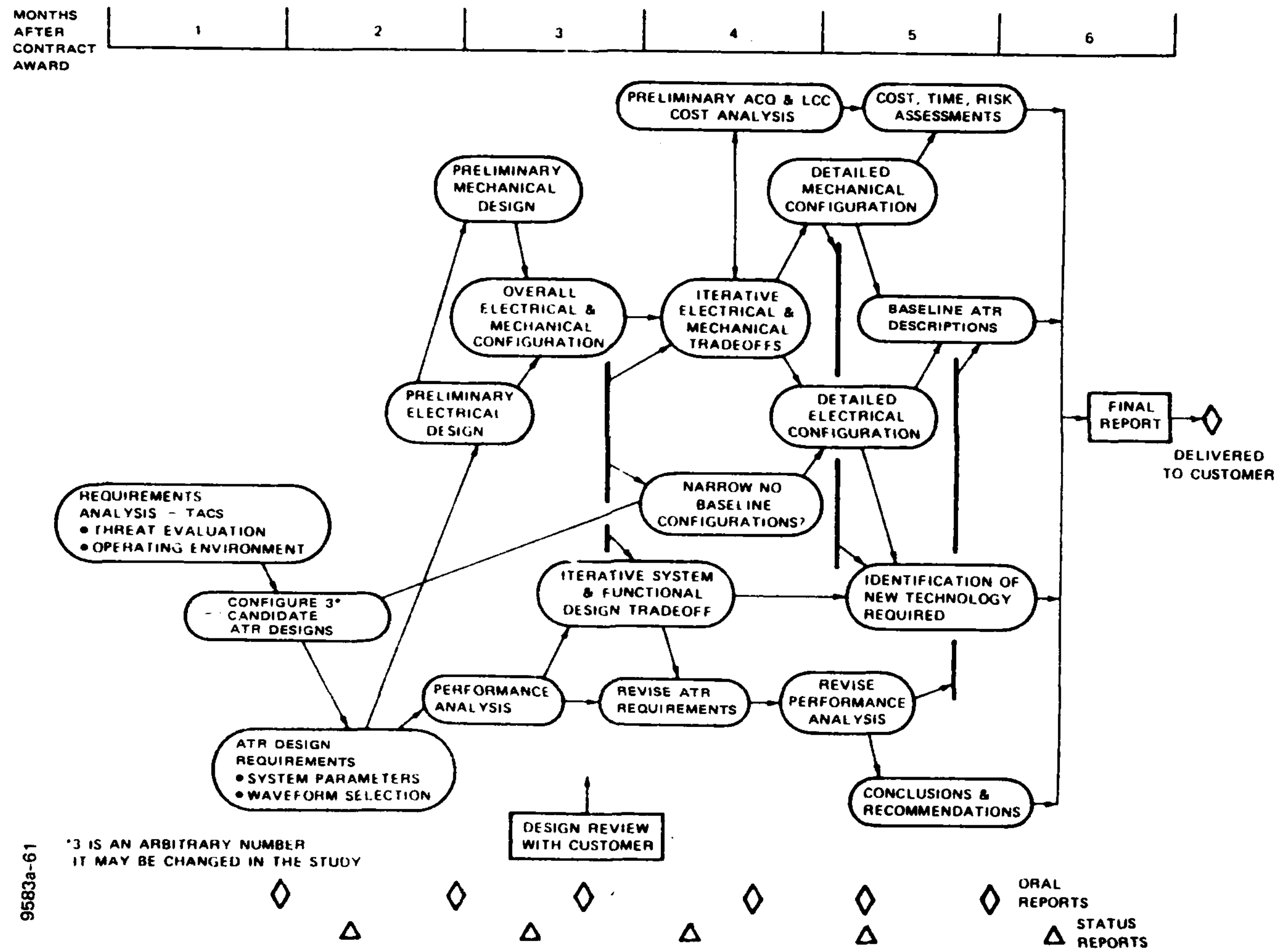

Figure A. Tactical radar technology study task flow network

The selected baseline ATR system configuration was subsequently analyzed in order to apportion specific requirements to the ATR's major subsystems (antenna, transmitter, receiver, signal/data processor, etc.). These subsystem requirements were then compared against what can currently be achieved by employing newly available technology implementations. The rationale for employing new technology implementation is that new technologies are typically on a steeper portion of the "capability improvements versus dollar expenditures" curve than are those based upon established older technologies. Where these new technology implementations were found lacking in capability, or were too large in volume, weight, power consumption, etc.; new technology advancements were identified and evaluated as to technical risk, cost, and required development time.

In parallel with these tasks devoted to identifying required subsystem technology advancements the ATR system requirements were further developed through studies concentrating on waveform and tracking requirements/implementations. These studies results in successfully bounding certain system parameters and in identifying additional tradeoff analyses that will be needed in order to define the optimum ATR. These studies can be found in Sections 4 and 5 of this report.

1.3 BASELINE ATR DESIGN CONCEPT

The design concept selected for the baseline ATR inherently provides the potential for satisfying all TACS/ATR requirements and is therefore the study reference needed to identify required technology advancements/cost reductions.

The baseline ATR design concept selected for the technology study is concisely depicted in Figures A and B. As shown in the figures, three self-propelled vehicles are used to transport the multifunction (search, track, and identification) ATR that provides long-range (200 nmi) hemispherical surveillance/identification coverage. Two of the vehicles transport identical equipments: two C-Band polarization agile antenna array faces with associated transmitters, receivers and signal/data processors. Since each array face provides coverage for a 90 degree azimuth sector, four array faces are needed to provide 360 degrees of azimuth coverage. The third vehicle transports a data/message processor, ground-to-air communications equipment, display(s) for autonomous back-up control, and the prime power source for the equipments on all three vehicles.

The baseline ATR's antenna design is undoubtedly the subsystem most strongly constrained by the TACS and ATR requirements. Perhaps the most important example of this premise is the high data rate requirement for track-while-scan (TWS) operation. Mechanically scanning antenna approaches were precluded by the data rate requirement and the desirability to inhibit visual detection. An electronically agile beam directing approach in both azimuth and elevation planes was therefore selected. Low sidelobes (-50 dB), particularly in the azimuth plane are needed to counter stand-off jammers and ARMs. Additional requirements for wide signal and operating bandwidths for LPI and non-cooperative target IFFN classification narrows the choice of design approaches considerably. Polarization agility on both transmit and receive should be implemented to afford improved performance in ECM and in non-cooperative target classification. To accommodate all of the above requirements/considerations the selected baseline ATR antenna design approach is a four face planar array having Rotman lens beamformers, and solid-state transmitters distributed in the elevation plane of each array face. Rotman lenses are used to achieve the true time delay beam steering necessary for wide signal bandwidth operation. This design approach has the capability of providing either single beam operation (the baseline implementation) or simultaneous multiple beam operation with adaptive beam shaping and null steering for additional capability. Null steering is an added ability to introduce well defined nulls (> -50 dB) in the antenna radiation/receive pattern in any arbitrary direction(s) for jammer nulling. This feature could be employed to minimize the ARM threat and significantly improve the ATR signal-to-jamming ratio.

The solid-state transmitter design selected for the ATR baseline accommodates the high data rate requirement by providing the capability for four simultaneous transmissions (and receptions), one from each face of the antenna array. It additionally provides the graceful degradation capability that is required and has the potential for providing "greater capability for fewer dollars expended," normally attributed to new technology implementations.

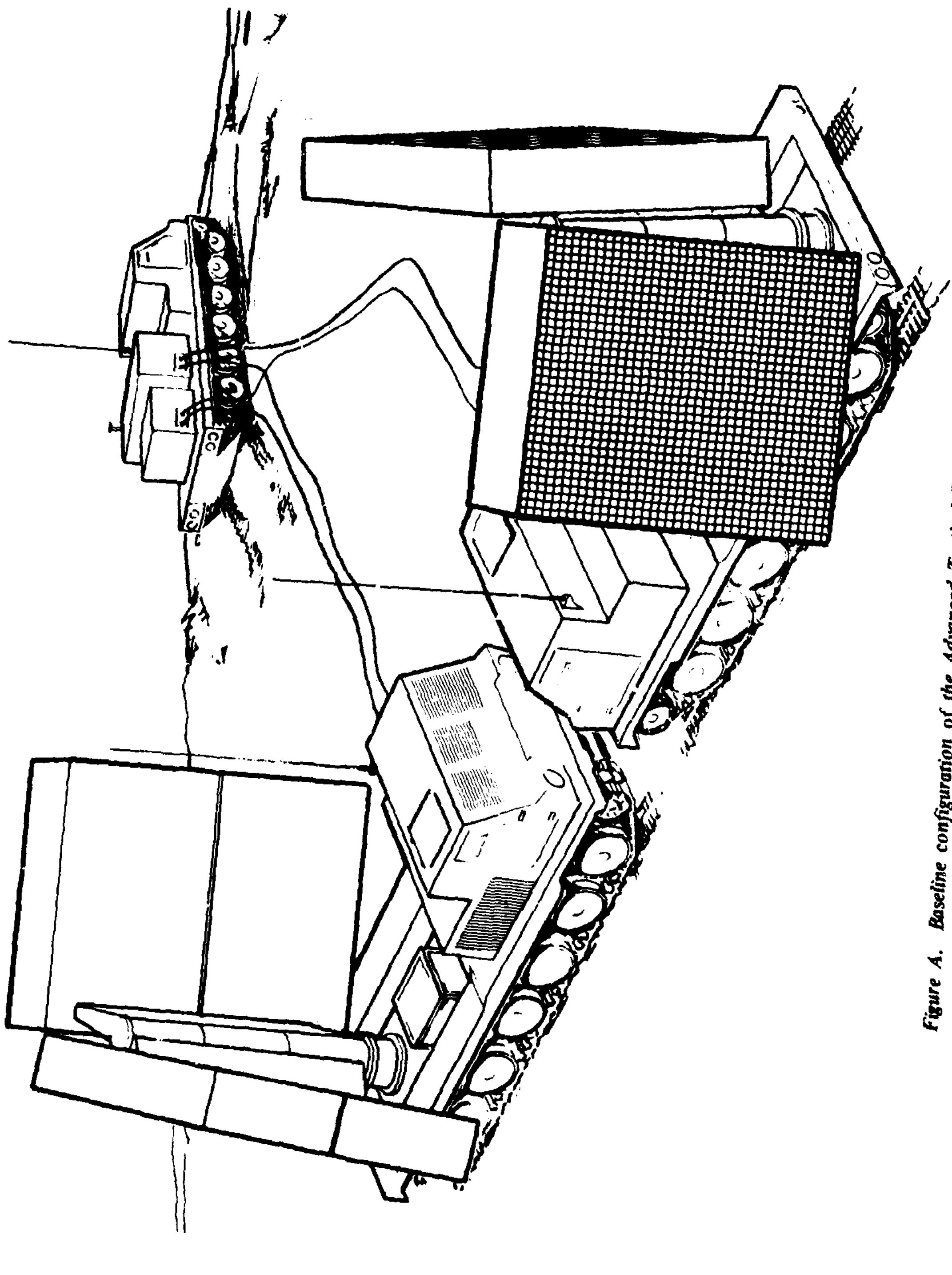

Figure A. Baseline configuration of the Advanced Tactical Radar

It is to be noted that the baseline ATR design approach could also accommodate a centralized solid-state transmitter design (less efficient) or a centralized tube transmitter (also less efficient and having greater weight and volume) if future performance-vs-cost tradeoffs dictate these implementations are preferred.

The essentially redundant (one per antenna array face) receiver and signal/data processor configuration selected for the baseline ATR is based on the trend in new thin/thick film (analog) and integrated circuit (digital) hardware technology toward dramatically reduced size and relative cost. The consequence of this trend is that redundant systems are both feasible and cost effective. The signal processor subsystem provides dual channel (H&V) polarization processing, adaptive spectral filtering, hard limited CFAR processing and binary phase coded pulse compression. Implementation assumes the use of VHSIC technology. The data processor subsystem provides target parameter (R, θ, ϕ) extraction, target tracking (automatic track initiation and maintenance), and target classification. The need for the design of a cost-effective multisensor adaptive system tracker is established and additional studies recommended. Recommended data processor implementation is through the use of modular hardware/software units being developed by ESD/RADC for TACS C^2 elements.

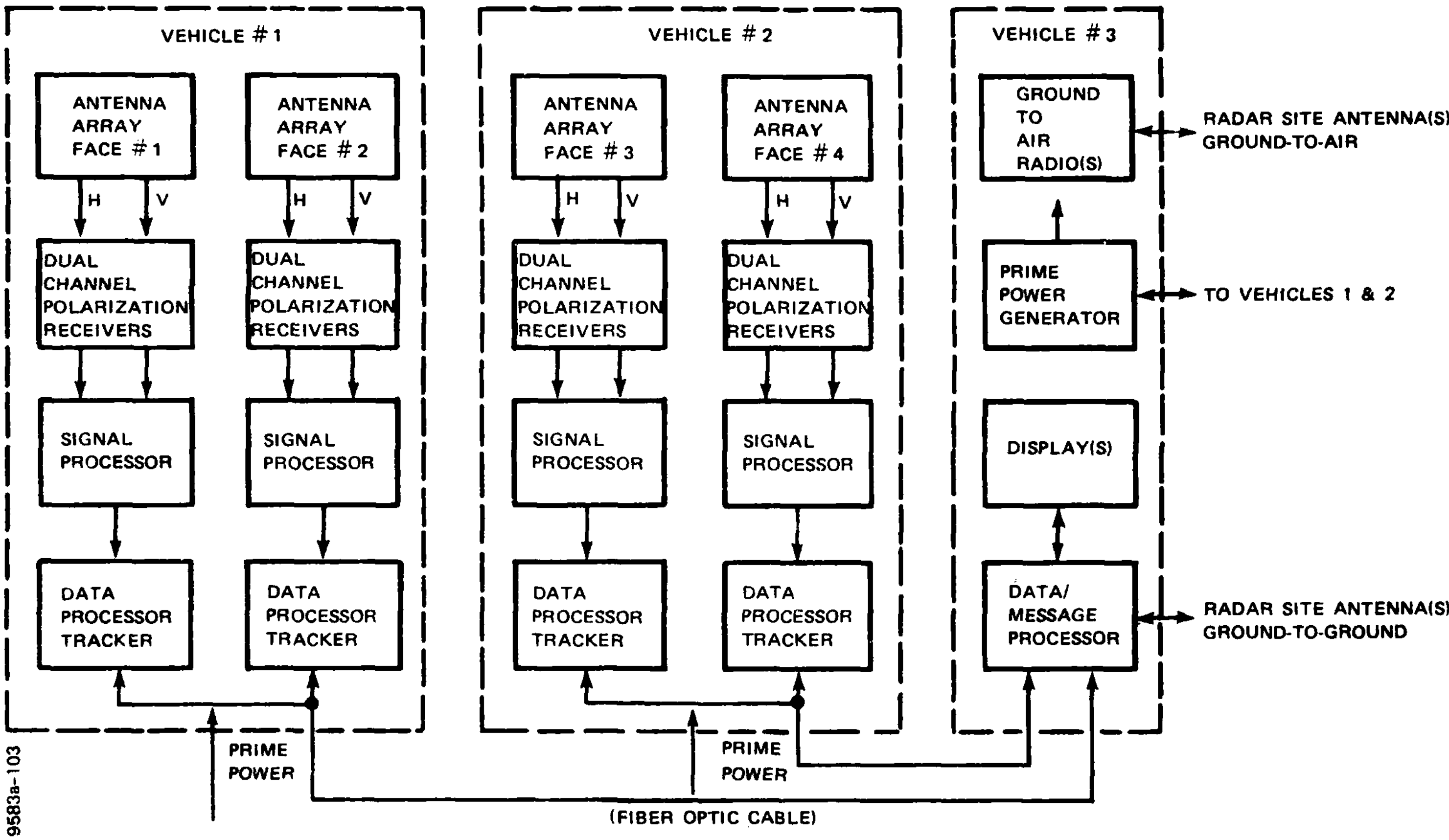

Figure B. Baseline ATR block diagram

1.4 REQUIRED COMPONENT TECHNOLOGY ADVANCEMENTS

Component technology advances are required for the Transmitter, Antenna and Signal Data Processor elements of the ATR in order to provide a cost-effective solution.

The purpose of this study was to identify the technology required to provide advanced multithreat performance capabilities in future tactical radar designs. To accomplish this, the baseline ATR system described in the previous section was assessed in terms of meeting the desired operational requirements utilizing existing technology. Deficiencies were noted either in meeting the operational performance and/or in achieving desired goals for size, weight, power consumption, and projected cost. It was concluded that advances both in component technology and in applied system methodology were required to bring these items into reasonable dimensions. The major component technology advances relate to solid state device development for the transmitter, correlator/memory/uncommitted logic arrays for signal and data processing, reduction of line and switch losses in the antenna, and lightweight material/armor development for general system weight reduction. Various trade studies were also recommended to evaluate alternate means of both hardware and system implementation to realize possible cost-benefit improvements.

The major radar elements related to the identified component technology requirements are:

- Antenna
- Transmitter
- Signal and Data Processor
- Mechanical Design

Table I summarizes the key component technologies for each radar design area, noting the particular devices involved, the desired requirement relative to existing performance, and a qualitative risk factor (low, medium, high) which indicates the inverse probability of success in meeting a post-1985 deployment schedule.

The antenna area lists three technology items needed to meet the desired performance in the field (-50 dB azimuth cardinal plane sidelobes, minimizing losses in the RF lines and switches, and maintaining and measuring electrical/mechanical tolerances). These issues are detailed in Section 6.1. The major risk item is achieving a less than 5 dB line/switch loss; roughly a 50 percent probability. The trade study required involves utilization of lower loss dielectric materials which will present potential packaging problems related to size and weight.

Table I. Component Technology Summary

Element	Component	Requirements	Existing Technology	Risk
Antenna	Rotman Lens Line/switch	< -50 dB az cardinal plane sidelobes	-40 dB	Low
	Line/switch losses	< 5 dB	7 dB	Medium
	Component tolerance	2-4° random phase stability	10°	Low
Transmitter	Solid state module	10 watt peak	2 watts	Low-Medium
		Low cost	Very high cost	High
	Tube	200 kW peak 10 kW average increased power margin	100 kW peak 5 kW average	Low
Signal Processor	Correlator chip	512 bits 6.5 MHz 6 mW/bit	64 bits 6.5 MHz 12 mW/bit	Medium
	Memory chip	16 K-bit RAM 75 nsec cycle 0.05 mW/bit	4 K-bit RAM 75 nsec cycle 0.10 mW/bit	Low
	A/D Converter	11 bits 6.5 MHz	8 bits 13 MHz	Low-Medium
Data Processor	Uncommitted LSI Logic Arrays	1000 gates 6.5 MHz	MSI/SSI	Low-Medium
Wideband Signal Processor	A/D Converter	6 bits 100 MHz	6 bits 30 MHz	High
	Memory	Shift Register 1K-bit 100 MHz	256 bits 40 MHz	High
	Uncommitted LSI Logic Arrays	500 gates 2 GHz	--	High

Table I. Component Technology Summary (Continued)

Element	Component	Requirements	Existing Technology	Risk
Mechanical	Composite Technology Transfer	Need for min. weight	Exists in other industry areas	Low
	Stripline Feed Prod.	Need hi prod rate to hold down costs	Can hand build small units	Low
	Lightweight Armor	Minimum wt to effectiveness ratio	6 to 8 lb/ft^2 for 100 grain @ 5000 ft/sec	Medium
	Threat Resistance Threshold	Need level specified to allow implementation	No specification exists	Low

1.5 REQUIRED SYSTEM TECHNOLOGY TRADE STUDIES

Various system trade studies are required to evaluate ATR variants permitted by the baseline concept.

While advances in component technology should lead to smaller, lighter weight, and more efficient ATR configurations, it is also reasonable to continue in the search for alternate means of implementation to improve cost/benefit performance. As noted in Section 1.2, the baseline concept should not be a constrained design. Within this context, various baseline technology issues have been identified as potential candidates for trade study evaluation. Most of these impact the waveform design and its related effect upon ATR performance and cost (see Section 4). Tracking technology also heavily influences system performance; this is detailed in Section 5. A summary of these and other related technology studies is presented in the paragraphs following and summarized in the Table.

System Technology Summary

Study Area	Cost or Performance Goals
Dual Channel Processing	Enhance clutter rejection 5 - 10 dB Reduce signal processor cost 50 percent
Spectral Filtering	Improve clutter rejection ~ 3 dB Enhance long range detection
Duty Cycle	Reduce processor cost 10 - 30 percent Improve multiple target discrimination
Wideband Processing	Potential for target classification and detection small cross sections in clutter
Monopulse Tracker	Increase update rate factor four balance against cost
Balanced Search/Track Design	Reduce processor cost 10 - 20 percent Improve track performance 3 dB
Multi-Sensor Tracker	Develop methodology for fusion of single sensor track data. Potential significant cost reduction radar module

Waveform Related Technology

There are four major waveform related areas identified for further study; namely, dual channel processing, spectral filtering, duty cycle reduction, and wideband processing.

Dual channel processing is designed to take advantage of the difference in the combined polarization and spectral scattering properties between targets and clutter, such that the probability of target detection is maximized. This could result in significant cost reduction in the Signal Processor configuration. Further study is required to determine the degree of target enhancement, and the trade between processor/receiver/antenna costs. The study would be followed by an extensive field test program. The technical risks in this area are considered low.

The general area of spectral filtering has undergone considerable study in efforts to enhance detection in clutter. This is particularly significant for the ATR in terms of long range detection and track through chaff. The list of specific study issues includes adaptive prf modes, beam forming techniques, and maximum entropy spectral estimation. Each of the above would entail a low risk study effort.

Duty cycle trade issues assume importance because the transmitted pulsewidth has a pronounced effect upon processor cost, as related to the waveform time-bandwidth product. Aside from cost considerations, the ambiguity plane responses for typical waveforms should also be evaluated in terms of performance associated with multiple target environments and raid size assessment. Selection of pulsewidth and duty cycle also impacts transmitter design, such that attendant trade issues involving solid state and tube type transmitters must also be investigated. As studies, these would also be considered low risk efforts.

Wideband processing is of interest in dealing with target recognition/classification, low probability of intercept waveforms, and in the detection of very small cross section targets in clutter. Although it was noted that a high risk exists for timely development of wideband logic devices, the evolution of techniques for wideband processing should proceed in anticipation of such development. With regard to detection in clutter, the trade issues involve the distributed nature of the target scatterers, and related effects upon false alarm and detection criteria in the various clutter environments. Target classification trade issues are discussed in the following paragraphs.

Single Sensor Considerations

In order to operate within the projected multithreat environment, the system must: (1) achieve a high level of automaticity, (2) possess a capability for adaptive resource management, and (3) capitalize on the synergism realized from netting of the system's sensors to obtain fast reaction to the threat. Target data and environment data must be used to continuously configure the system into a format which optimizes target extraction, target track, and target classification. In this manner, the processing resources are always balanced so that excessive demands will not have to be made on the performance measures of any one subsystem. Within this framework, a key factor is that operation of the autotrack process feeds back and directly impacts the operation of all of the other processes.

The major concern for the transmitter involves the availability of a device operating a C-Band, which will achieve the required power demands at reasonable cost in a solid state configuration. Existing modules have nominal 2 watt peak power capability, requiring 25,000 of these devices to deliver a peak power of 50 kW. It is expected that a 10 watt device would be available for post-1985 deployment. The concomitant risk of achieving a 10 watt module at an acceptable cost is, however, high. On the other hand, transmitter tubes currently exist which can supply the required baseline power. In addition, a low risk development effort should result in higher tube power capability for increased system performance and/or power margin. The relative merits of solid state versus tube designs are more fully explored in Section 6.2.

The signal and data processor advanced technology requirements noted in Table I, relate primarily to device development leading to reduced size and power consumption. It is noted in the processor description of Section 6.4, that the electrical requirements for baseline operation can be met with existing components. However, reductions in size and power consumption of 50 percent are necessary to meet desired goals. The major item noted is the correlator ship which involves about 35 percent of the signal processor architecture. This carries a medium risk label because specialized development would be required for the ATR system, although the DOD VHSIC program could possibly also contribute toward this development. The remaining items of A/D converters, memory chip, and LSI uncommitted logic arrays are in a lower risk category. Although some development is required, it is expected that other requirements for both the military and commercial markets will provide sufficient demand to spur production of these devices.

Wideband signal processor devices are concerned with special radar applications for target recognition and/or classification. It should be noted that these functions are desirable but not necessary to meet the baseline requirements. Although there are on-going efforts in this area, the risk of meeting the wideband processor requirements by 1985 is considered high because the devices will require gigabit switching speeds for proper operation. This is discussed in greater detail in Section 6.4.

The last set of items identified for component development is in the area of mechanical design. Three of the four technology improvements are needed to improve the mobility performance of the system. The establishment of threat resistance leads to armoring requirements and to a suitable mix ratio between advanced composite materials and armor, such that an equitable balance can be established between mobility and survivability. Lightweight armor development is currently under investigation within the industry, and represents a medium risk factor for producing material superior to the present ceramic/Kevlar combination. The remaining three items are low risk development/study efforts. Additional details can be found in Section 6.5.

The other critical aspect of the autotrack process is that its output represents the major radar sensor data interface with the tactical user. As such, an ancillary theme to the above is that single system tracks (SST) have to be established and identification determined using all target data derived from all sensors in a timely fashion. The netting or merging of target data is the final operation upon which the tactical user depends.

The issue of optimum energy/resources control becomes especially crucial for multifunction radar embodying both search and track. From the tactical user viewpoint, timely assessment of the threat is fundamental to the optimum allocation of weapon resources. In effect, the level of automaticity realizable is critically dependent on the efficacy of the target classification function. If the variances associated with the target classification outputs are minimal, then a high level of automaticity is feasible resulting in decreased system reaction time. However, a critical facet that impacts the efficacy of the target classification function is the degree of adaptiveness that the surveillance radar possesses, (e.g., variable track verification data rates).

It is essential, therefore, that track initiation be accomplished with a minimum of "looks" per target, and that false or redundant tracks be minimized. This can be facilitated by proper distribution of false return rejection among the various radar processes, and the utilization of special wideband waveform modes to enhance the classification of targets of interest.

The above discussion represents major technology radar design trade issues from which the following specific SST trade studies are recommended for further investigation.

- Reexamine allocation of search/track functions to provide balance resource operation. For example, optimization of the single sensor track function can result in a reduction of signal processor requirements such as false alarm and target detection figures-of-merit. Power requirements may also be reduced after track, permitting enhanced surveillance capability. Development of accurate state estimation techniques, assocation algorithms, and variable data rate capability is essential to this study effort.

- Target classification is a key function for track verification and threat assessment (see Section 5.8). A study task is recommended for the development of target classification algorithms using wideband signature data including a polarization discriminant. The major objectives include determination of signature variation with aspect, required sampling rates, and feature selection for operation in chaff and in a multiple target environment.

- Investigate cost/performance relationship for monopulse tracker as compared to baseline sequential lobing technique, to increase rate of track update.

Multi-Sensor Tracker

The magnitude of the threat environment dictates the necessity for a multi-sensor network track function.

The requirement for a multisensor adaptive system tracker poses additional technology trade study possibilities regarding techniques for optimally combining the outputs of the individual radar sensors. The mechanization of a system track function will also influence the design of the local track process, which, as noted before, has an iterative effect upon the balanced design of the other radar processes. Consequently, the design approach for the system tracker will have major impact upon the requirements and costs of the individual radar (i.e., possible utilization of less than four antenna faces per sensor).

The underlying problem in this area is that the technology for adaptive system track functions has not as yet been developed in terms of a formalized methodology for generic track-while-scan surveillance radars. Formulation of this function should receive high priority (see Section 5).

The major tasks needed to be performed to develop a methodology for multisensor adaptive system trackers are:

- Perform operations analysis and develop performance figures of merit
- Perform data integration trade-offs
- Establish registration error budgets
- Coordinate system trade-off analysis
- State estimator optimization analysis
- Association optimization analysis
- Initiation and deletion optimization analysis
- Design computer simulations
- Perform cost-effectiveness trade-offs
- Perform military worth analysis
- Design system tracker
- Perform evaluation of system tracker.

The last five items are included to complete the process leading from operations analysis to an engineering design and the performance evaluation of that design. The complexity of the problems are such that computer simulations will be necessary to perform the operations and optimization analysis for each of the track functions. Additional computer simulations will be needed for the trade-off analyses and performance evaluations.

1.6 CONCLUSIONS AND RECOMMENDATIONS

The baseline ATR design can potentially satisfy TACS requirements for single multifunction sensor elements of an integrated multi-sensor net. Component technology advances and additional system trade studies are needed for this potential to be realized.

A summary of identified technology advancements required for post-1985 deployment of the ATR has been presented in the previous sections. As noted, the baseline design concept has the potential for satisfying the TACS/ATR requirements, where most of the identified required component advances relate to size, power consumption, and cost. Deficiencies in projected multi-function operation are more illusory, since the ultimate requirement for single sensor performance will be heavily weighted by the design concept of the multi-sensor network. It is, therefore, strongly recommended that the more global requirements be definitized as early as possible, since they will influence specific cost trade issues of the ATR. Regardless of this, there are various key component and/or system cost trade studies which should be undertaken for single radar sensor design. The recommendations that follow are associated with the more important and higher risk items noted previously.

Component Development

- Antenna line and switch loss reduction and packaging
- C-Band solid state transmitter module development
- Correlator and uncommitted LSI logic array development
- Gigabit logic development for A/D converters, memory, and uncommitted logic arrays
- Lightweight armor development

System Studies

- Dual channel polarization processing techniques
- Spectral filtering enhancement
- Waveform selection, duty cycle trade issues in multiple target environment
- Wideband processing for target classification
- Multifunction search/track trade study to optimize radar resources
- Development of multi-sensor track methodology

Section 2

POSTULATED THREAT ENVIRONMENT AND OPERATIONAL REQUIREMENTS

2. POSTULATED THREAT ENVIRONMENT AND OPERATIONAL REQUIREMENTS

2.1 CURRENT AND FUTURE THREATS

The U.S. Tactical Air Force in the post 1985 period will need Air Defense Weapons Systems and a Tactical Air Control System (TACS) that have been optimized to operate effectively in a threat environment predicted to be both sophisticated and multifaceted.

A major threat to the future TACS and its Advanced Tactical Radars (ATRs) has been attributed to Soviet ARMs that can home on RF emissions. The ATR total threat environment, however, encompasses RF, IR and E/O guided weaponry and the Electronic Warfare (EW) ancillary equipment supporting these weapon systems. As a minimum, the EW equipment includes detection systems (ESM) capable of providing parametric radar identification and target site location, and jamming systems (ECM) capable of providing brute force (denial) and deception jamming. Aircraft of the Tactical Air Forces (TAF), which provide one source of protection to the TACS complex, will themselves encounter enemy SAM and AAM weaponry and jamming.

The current utilization of satellite reconnaissance and the introduction of advanced missiles (cruise and anti-radiation) and precision guided munitions demonstrate a level of Soviet threat development capable of engaging airborne TAF and land-based TACS complexes with significant efficiency.

In a postulated Soviet Pact forces engagement scenario, the TACS key active elements and their functions will be located by a variety of reconnaissance and surveillance equipments prior to any airborne penetrations and strikes. Weaponry and preferred penetration routes will be selected and ECM requirements for both the strike and support aircraft will be established. Diversionary and actual chaff corridors may be sown to serve as penetration aids; and, IR suppressants and IR/RF decoys may also be used to provide penetrating aircraft protection and increase confusion of the target selection process of our own air defense network. It is likely that these decoys and RPVs will employ ARM guidance against specific TACS emitters. Low cost expendable jammers could also be employed to perturbate the TACS complex. Communications and IFF jamming will be extensive and will be supplemented by barrage and spot jamming from stand-off support aircraft. Various forms of spot and repeater jamming will be used for self-protection by penetrating aircraft. Data link jamming may also be employed to degrade command guidance and defense aircraft vectoring. The intent of these efforts will be to minimize the TACS reaction time to ARMs and other strike weaponry by decreasing the ATR's detection range, and thereby maximize hostile weapons' effectivity.

2.2 TACTICAL AIR CONTROL SYSTEM OPERATIONAL/CONFIGURATIONAL REQUIREMENTS

To successfully perform its mission, the future worldwide deployable TACS must meet specific operational and configurational requirements.

The mission of the TACS is (1) to maintain surveillance of air activities within the theater of operations, (2) identify all aircraft operating in the area, (3) coordinate, control and regulate the activities of all friendly aircraft, and (4) maintain the integrity of the air space to the extent specified by the Air Force Component Commander. To accomplish the mission in the severe threat environment predicted, TACS elements must meet certain functional criteria. These functional criteria dictate both operational and configurational constraints/requirements. A qualitative summary of these requirements is contained in the paragraphs following.

Complete Air Situation Picture

The TACS sensors must provide a reasonably accurate and complete picture of the air situation over the theater of operations to serve a hierarchy of users. Users should be able to extract reliably and easily the specific information that they need for their missions. Thus, all elements (radars and op centers) of the system must be capable of automatically tracking and reporting track information without the need for manual intervention. The system must also be able to track a large number of maneuvering targets and maintain proper track identity of crossing tracks. Furthermore, the system must be capable of forming single system tracks from multiple sensor sources.

Identification

The system must resolve the dual problem of fratricide and resource allocation. The fratricide problem requires targets to be identified as friend, foe or neutral with a high probability of correct identification in the presence of heavy electromagnetic interference. The resource allocation problem also implies that targets must be further resolved as to type (bomber, fighter, missile, helicopter, etc.), raid size, stores and probable missions. The system must provide the means of identifying all targets in the theater of operations using a low number of independent tries, in day and night operations, in all types of weather, and at all operational altitudes.

Graceful Degradation

The system must be able to fulfill its mission while under determined hostile physical and electronic attack. Implicit in this definition are additional requirements for survivability of system elements, redundancy, and back-up modes of operation. Survivability implies both functional survivability as would be needed in the ECM environment, and operational survivability as would be needed in a direct attack situation. Thus, the system must not only be able to detect ARMs, employ appropriate countermeasures, and not fail catastrophically in a jamming environment but must continue to provide adequate track information.

The system must provide overlapping sensor coverage and redundant communication links to insure functional integrity in the event of system element loss. Back-up modes of operation should be provided to enable remaining sensor and communication elements to continue to perform critical mission functions under reduced capability.

Air Transportability

The elements of the TACS must fit inside available TAC and MAC transport aircraft. In addition, the complete TACS must be delivered with a minimum number of aircraft flights.

High Mobility

High mobility in all terrain (both on and off-road) is required of all TACS elements. This is necessary in order to deploy quickly within the threater, to reconfigure quickly to accommodate disabled or augmenting elements, to minimize down time due to repositioning, and to enhance element survivability by complicating the enemy's targeting problems. All elements of the system must be capable of rapid teardown when required to move and be able to set up quickly and reestablish operations and communications with other elements.

Flexibility

Flexibility is required to enable the system deployment to meet theater specific requirements. Implicit in this requirement is the ability to vary the number and types of sensors and their interconnections. The system must be configured so that it can function autonomously in any theater of operation and/or augment an existing U.S. or allied system.

Growth Potential

The TACS must not become obsolete due to an inability to incorporate technological improvements to elements or sub-elements. An example of how growth potential can be assured is by adopting a modular approach to C^2 system acquisition where common hardware and software modules and a flexible interconnect subsystem are used in the design and fabrication of the C^2 systems.

Logistically Supportable

The TACS configuration must be realistically supportable in terms of required maintenance, manning including training, reliability, peripheral support equipment and number of unique system components. The surveillance elements (ATRs and operations centers) must be sufficiently reliable and perform without routine manual involvement so as to permit continuous operation although minimally attended.

2.3 ADVANCED TACTICAL RADAR DESIGN REQUIREMENTS/GOALS

2.3.1 THREAT IMPACT ON RADAR DESIGN

The next generation tactical radar must not only feature greatly improved performance in a benign environment, but must also be functionally and operationallv survivable in the projected threat environment of the 1990's.

A number of future TACS concepts and system architectures are currently being evaluated by the Air Force to overcome some of the present system's identified deficiencies and effectively counter the postulated threat. These concepts range from simple alterations of the existing TACS architecture by augmentation and integration with companion systems, to replacement of the entire TACS with new elements. Many of the alternatives being evaluated employ a new long-range ground based tactical surveillance radar as the primary sensor element supporting the AC&W functions of identification, GCI, air traffic regulation, etc. Since this advanced tactical radar (ATR) must be capable of performing its functions in the projected threat environment, its design must be directed to provide excellent ECCM and anti-ARM capability.

The ATRs design will have to cope with and effectively counter two basic hostile activities, jamming (denial including chaff and deception) and direct attack by weapons (ARM, PGM, etc). To minimize the effects of jamming, the following ATR characteristics must be carefully selected:

a) Operating Frequency

b) Antenna Sidelobe Levels

c) Multi-Dimensional Resolution

d) Power-Aperture Product

e) Displays

f) Waveform Design

g) System Flexibility

h) Complementary Equipment and System Integration

i) Passive Search and Track

j) System ECCM Management

k) Data Links

l) Covert Operation.

Fortunately, many of the ATR design decisions that should be made to counter the effects of jamming also help to counter the effectiveness of ARM/PGM systems and supporting ELINT systems. For example, decisions affecting ATR frequency selection, sidelobes, waveforms, system flexibility, complementary equipment and system integration, and passive search and track benefit both ECCM and anti-weapons capabilities. However, choices of power-aperture product and signal processing for data displays can be antithetical to simultaneously achieving these two capabilities. It is therefore necessary that both requirements be considered in concert when selecting the ATR design characteristics.

Operating Frequency

The selection of operating frequency is strongly influenced by the mobility and transportability requirements of a truly tactical system. The other considerations are performance related – namely detection and tracking in a clutter and ECM environment. A more complete discussion of the rationale for operating frequency selection is found in Section 3.2.

Antenna Sidelobe Levels

Some types of jamming (stand-off jammers and some forms of deception jammers, such as sidelobe repeaters) will be critically dependent on the receiving or transmitting antenna sidelobe patterns of the ATR to be effective. In addition, ELINT locating systems and ARM guidance systems will, to a great extent, be dependent on the energy transmitted via the ATR antenna's sidelobes. Therefore, both transmit and receive sidelobes of the ATR should be as low as practical, e.g., $\leqslant -30$ dB in the elevation cardinal plane, $\leqslant -50$ dB in the intercardinal regions and azimuth cardinal plane.

Multi-Dimensional Resolution

High resolution in range, angle, and radial velocity should be provided by the ATR to reduce the effects of clutter and to facilitate automatic target track initiation/maintenance. Track data will be useful in the elimination of some forms of spoofing but more importantly, will be required for threat identification/evaluation processes and to provide a residual control capability at the ATR site in the event of operation center loss. The use of polarization control on transmit and receive shows promise for suppressing clutter and jamming and possibly facilitating classification and identification of hostile threat targets. Provisions for polarization control in the ATR should therefore be considered.

Power-Aperture Product

In the ATR versus jammer encounter a large radar power-aperture product is most desirable. In the ATR versus ARM encounter, the lower the radar peak power radiated, the more difficult it will be for ELINT targeting and the ARM's acquisition system to lock-on to the ATR at a long stand-off range. Therefore, only that level of peak and average power should be provided that insures the required detection of non-jamming, mutually-screened targets. It is also desirable that the ATR have the ability to actively detect self-screening targets (by employing a burn-thru mode at the possible sacrifice of coverage) at critical moments of encounters.

Displays

Although ATR operations must be largely automatic due to short reaction times, it should be recognized that an experienced human operator could contribute greatly to the successful outcome of any hostile engagement. Automatic operation infers the need for CFAR processing to discriminate against undesired signals such as clutter and jamming. Unfortunately, CFAR processes generally subserviate the probability of target detection in deference to the maintenance of CFAR. Consequently, it is recommended that the ATR incorporate both CFAR and non-CFAR processing with appropriate displays for an operator to view. These displays should permit the operator to determine the extent of ATR surveillance degradation resulting from jamming, determine the source and various kinds of jamming present, and report his appraisal of the situation with operational recommendations to the appropriate C^2 components of the TACS.

Waveform Design

A countermeasure that is very effective in providing the ATR with good ECCM and anti-ARM capability is a broad signal bandwidth waveform having low amplitude or peak power. Such a waveform will have a low probability of intercept (LPI), especially in a multi-emitter environment. The broad signal bandwidth effectiveness is due to the increased range (time) resolution. A waveform having a signal bandwidth of at least 10 MHz should be used with the ATR to reduce the radar range resolution cell (and therefore the clutter/jamming intake) to the range extent of typical airborne targets (approximately 50 feet). Phase coding/pulse compression is recommended to achieve the required target detection with a long (277 μsec), low amplitude (50 kW peak) transmitted pulse waveform. The use of the long pulse with a purposely degraded rise time will insure the existence of multi-path interference, thereby decreasing ARM accuracy. To insure that jamming sources and ARM guidance receivers are forced into broadband operating modes, the ATR waveform should also have the capability of pulse-to-pulse frequency agility over as wide a portion of the operating band as practical. In addition, to insure that the ATR waveform is difficult to anticipate and repeat it should have coding, PRF and pulsewidth agility.

System Flexibility

The TACS must be able to respond to theater specific requirements which demand deployment of various numbers and types of sensors and interconnections. Additionally, the TACS must be capable of functioning autonomously by performing the functions of identification, GCI, air traffic regulation, etc. This requires the ATR to have its own track computer for storing and exchanging track information with other ATRs as well as for reporting all tracks to TACS operation centers. These operations centers will be the primary C^3 elements and may, or may not have ATRs co-located with them. Autonomous control capability will exist at each ATR as a backup mode in the event of loss of one or more operations centers. As such, each ATR site must be able to communicate with aircraft. This communication may include both voice and data which would provide the capability of transferring the air situation display to the aircraft computer. The number of ATRs associated with each operations center as well as all TACS operations centers will be netted with each other.

The ability of a stand-alone ATR to provide undegraded surveillance in the ECM environment postulated and guaranteed survivability against the ARM/PGM threat can most probably be categorized as wishful thinking. More realistically, the total sensor net of the TACS (including ATRs, short-range gap fillers and the E-3A AWACS) and other available theater resources (such as the Army Air Defense System) will be required to provide effective surveillance, control and survivability. Thus, the ATR design should be sufficiently flexible to accommodate theater specific requirements which may include: (1) bi-static or multi-static operations, (2) all altitude gap filler operations, and (3) spoofing and/or decoy operations. All of these operational modes would be in addition to the ATRs normal mode of long-range monostatic surveillance.

Complementary Equipment and System Integration

TACS/ATR survivability in the projected threat environment necessitates a real-time coordinated response that can only be achieved through the integration of complementary active and passive sensors, ESM, passive defense measures, hard-kill weapons, and command and control elements.

It is postulated that the combined resources of the future TACS including the weapons systems under its control, will be required to effectively counter the projected ARM threat. Furthermore, critical reaction time considerations will mandate real time threat data processing and control of all available countermeasures

A suggested preliminary solution to the problem of countering the ARM entails a three-step approach:

a) ARM detection and identification

b) Threat Assessment

c) Application/control of countermeasure(s)

In order to apply the most effective countermeasures, the ARM weapon system (preferably the missile's launch platform) must be detected and identified at the earliest opportunity in an engagement (preferably the pre-launch phase). The process will be difficult due to the projected long stand-off range capability and the variety of ARMs and guidance techniques that could be encountered. Effective countermeasures for one type of ARM system may not be effective against another type and, in fact, may inadvertently enhance the other type of ARMs capability. Therefore, it is extremely important to correctly identify all ARMs and types that are involved in an engagement and to assess the composite threat that is presented. In solving this problem it is postulated that a number of sensors (active/passive) and processing algorithms must be employed to formulate the composite threat picture by direct identification or a process of elimination. The sorting parameters for this process can be provided by ATR target track information, passive sensors detections and identification of hostile RF, IR and laser emissions, real time and "a priori" tactical intelligence information inputs from other TACS C^2 centers, and threat flight profiles and tactics information. After a positive or probable threat identification and situation assessment is made, the most effective countermeasure(s) available in the TACS can be selected. The countermeasure resources available could include special modes of ATR operation, ESM transmissions for ARM seeker angle deception and/or noise jamming, IR and E/O countermeasures, and hard kill defense weaponry.

Passive Search and Track

Although jamming identification and passive angle track (jam strobes) will be provided in the ATR, this capability is normally limited to the situation where the radar finds itself unable to operate normally (skin track). A more general capability is recommended for the ATR by tuning to hostile RF emissions and tracking them passively for threat evaluation and direction of responsive friendly weapons systems. In addition, passive IR and E/O sensors are also recommended to be employed at the ATR site.

The ATR can also be employed as a passive jammer locator. For this application two or more ATRs, deployed along a suitable baseline, can locate a jamming source by multilateration. In a multiple jammer environment correlation techniques must be employed to eliminate spurious responses or "ghosts." Sampling would be employed to minimize the total channel bandwidth between ATRs. A separate study would indicate the extra equipment needed to provide passive jammer location.

System ECCM Management

An effective ECCM/anti-ARM capability can only result from the judicious selection of ATR parameters, operating modes and processing techniques to evaluate and counter the threat in a near real-time situation. It is not sufficient to simply minimize the effects of jamming if at the same time unacceptable target detection or tracking performance is incurred. This situation could very easily result in destruction of the ATR by ARMs/PGMs.

The ATR should therefore exhibit flexible operational capabilities that can be advantageously applied in response to ECM analysis and threat evaluation. An example of flexible parameters to be incorporated include polarization control, pulsewidth, pulse code, prf, and frequency. Modes to be considered include burn-through, search, track, decoy/spoof, bi-static. Processing techniques include CFAR, non-CFAR, polarization, MTI, and non-MTI.

Control of the ATR's parameters, modes and processing techniques should, to a great extent, be automatic and adaptive. An ECCM operator could be employed advantageously, however, in analyzing the threat situation and providing assistance in optimum ECCM selection for those situations when unlikely combinations of ECM are encountered.

Data Links

The vulnerability of the data links between the ATR and the TACS C^2 operations centers compromises the ATRs function. These data links will, most assuredly, be assaulted by ECM. Redundant communication means should therefore be considered. Certain deployments could utilize fiber-optic links between radars and operation centers.

Covert Operation

The ATR design should be such that it is less vulnerable to signal exploitation. Techniques employing wideband digitally coded transmissions at low peak power should be adopted so that less useable information is supplied to exploitation receivers at long-range. Multi-static operations and spoofing operations should also be considered to confuse enemy ELINT systems.

2.3.2 OPERATIONAL REQUIREMENTS IMPACT ON RADAR DESIGN

The baseline ATR design requirements/goals are derived from the future TACS operational/configurational requirements.

The baseline ATR design requirements/goals and technical implementation parameters, Tables I and II, were derived from the TACS mission and operational/configurational requirements. The TACS operational requirements consist of those factors which relate to meeting the mission requirements after the TACS is in place, and the configurational requirements are those requirements which relate to the system logistics problem.

Preliminary environmental requirements, which have been compiled from relevant military specifications for tactical systems and modulated by our own best judgement, are found in Table III.

Table I. TACS Operational Requirements/ATR Design Requirements

TACS Operational Requirement

1. Air Surveillance Coverage

   All theater, all weather (typical theater 200 nmi x 250 nmi)

   Threat Environment – ECM, ESM, ARM, PGM, etc.

   Target Environment-hostile and friendly aircraft, helicopters, missiles, RPVs.

   System Track – 5000 targets

   Raid Size – 2500 targets

   Attack Corridor – 10 to 20 nmi wide

ATR Design Requirement/Goal

Required function – Normal Monostatic Surveillance Mode (Automatic search/detection, track, ARM threat warning [ARM alarm])

Surveillance Coverage

Azimuth:	360°
Range.	200 nmi (Benign Environment) 100 nmi (ECM Environment)
Elevation:	-1° to +20° search -1° to +60° track +3° to +90° ARM alarm
Altitude:	200 ft to 100 kft
Data Rate:	⩽ 10 sec search ≧ 2 sec* track ⩽ 3 sec ARM Alarm

Target Resolution

Range:	30-50 ft (for coarse raid size determination)
Angle:	Required values determined by clutter models and signal/clutter processor implementation

*Precise rate determined by target maneuvers, crossing tracks and tracker implementation.

Table I. TACS Operational Requirements/ATR Design Requirements (Continued)

TACS Operational Requirement	ATR Design Requirement/Goal
1. Air Surveillance Coverage (Continued)	Target Resolution (Continued) Radial Velocity: Required values determined by clutter models and signal/clutter processor implementation Target Position Accuracy: Required values determined by tracker implementation and interceptor requirements. Radar Site Surveillance Capability Track File Capacity: 1000 tracks Local Tracks: 200 tracks Raid Size: 500 targets Jammer Location: 50 jammers
2. Identification IFFN all targets in the theater All weather, day/night threat environment IFFN – 5000 targets/tracks	Required Function – ID measurement mode to support Theater-Wide Unified Aircraft ID System (TWUAIDS) Probability of Correct ID approaching 0.99 Time Required for ID – ≤ 10 sec after target detection/designation Level of ID – IFFN, target type, probable mission Implementation External Systems: JTIDS; Improved Beacon System; Flight Plan Data Base Internal Systems: Flight Plan/Track Matching; Non-cooperative signature technique via polarization and spectral analysis Radar Site ID Capability ID Capacity: 200 targets/tracks

Table I. TACS Operational Requirements/ATR Design Requirements (Continued)

TACS Operational Requirement	ATR Design Requirement/Goal	
3. Graceful Degradation	Required Functions –	
Maintain Acceptable Air Surveillance/ Identification in threat environment	Back-up Op Mode:	Autonomous threat warning, GCI, Air traffic regulation, etc.
	Bistatic Op Mode:	Passive receive only
	Spoofing/Decoy Op Mode:	Transmit only
	Burn-through Mode:	Selected targets
	Physical Survivability –	
	Hardened Antenna:	Advanced composites and lightweight armor
	Critical Component Redundancy:	Antenna, transmitter, receiver, processor
	High Mobility:	Tracked/wheeled armored vehicle sensor platform
	Functional Survivability –	
	ECM Rejection:	$\leq$ -50 dB antenna sidelobes Polarization agility/processing CFAR/non-CFAR processing $\geq$ 10 MHz signal bandwidth Frequency, pulsewidth, pulse code, PRF agility
	Chaff/Clutter Rejection:	Adaptive signal/clutter processing
	ESM/ARM Denial:	Low probability of RF/IR/EO Intercept $\leq$ 50 kW peak pulse $>$ 277 μsec pulsewidth
4. Air Transportability Transport Aircraft C-130, C-141, C-5A	Number of Flights for ATR and Related Equipment	$<$ 3

Table I. TACS Operational Requirements/ATR Design Requirements (Continued)

TACS Operational Requirement	ATR Design Requirement/Goal
5. High Mobility	ATR Vehicle
All terrain	Type: Tracked/wheeled Armored vehicle
	Number Required: ≤ 3
	Speed: ≥ 40 mph
	ATR Set Up Time: ≤ 15 minutes/3 men
	ATR Tear Down Time: ≤ 5 minutes/3 men
6. Flexibility	Desired ATR Operational Modes:
Modularity to accommodate theater specific requirements	LR Monostatic Surveillance 360° or Sector Operation LR ID Measurement SR to MR Gap Filler Autonomous Control Bistatic/Multistatic ECM-jamming, spoofing, decoying Passive jammer location
	Min. ATR Site Modules –
	Sensors: 2 identical modules (each capable of providing 180° azimuth coverage)
	Prime Power/Ops Center: 1 module (provide autonomous site control as back-up)
	Comm: G-A: JTIDS data link with voice back-up Ground – digital link plus backup to neighboring radar sites and Op Centers Fiber optic links intrasite
	Augmented ATR Site Capability –
	Incremental module additions will increase physical and functional survivability and permit simultaneous multi-modal operations.

Table I. TACS Operational Requirements/ATR Design Requirements (Continued)

TACS Operational Requirement	ATR Design Requirement/Goal	
7. Growth Potential	ATR Site Modules defined above under Flexibility	
Functional Modularity Within ATR Site Modules	Define functional modules for:	
Capability to add new/improved site modules or functional modules within site modules.	Sensor antenna Sensor receivers Sensor processors – signal, data, data base Prime power Communication	
	Devise flexible ATR site intraconnect subsystem	
8. Supportability	ATR Unit Cost:	⩽ $8M
Cost effective 15 year LCC	Personnel Required:	3 level 1
	Reliability:	⩾ 2000 hour MTBF
	Maintainability	⩽ 30 min MTTR
	Prime Power:	⩽ 100 kW

Table II. Baseline ATR Technical Parameters

1. Frequency	S or C-Band
Frequency Agility Bandwidth	⩾ 400 MHz
Signal Bandwidth	⩾ 13.3 MHz
2. Power	
Peak RF Pulse	⩽ 50 kW
Average RF	⩽ 5 kW/Antenna Face 20 kW – 4 Faces
Prime Transmitter	70 kW (> 25% efficiency)
Auxiliary	30 kW
Total Power	⩽ 100 kW
Mechanical Power	170 HP (80% efficiency)
3. Antenna	
Type	4 Face Planar Array (2 Faces/Vehicle)
Aperture Size	160 $ft.^2$ ($15m^2$) each face
Bandwidth	⩾ 400 MHz
Data Rate	⩽ 10 sec for 360° azimuth search ⩽ 2 sec for precision track
Pattern	Boresight beam 1.16° az X 1.05° el ⩽ -50 dB sidelobes inter cardinal and azimuth cardinal ⩽ -30 dB Elevation cardinal
4. Signal Processing and Waveform	Ground Clutter Rain and Chaff Barrage Jamming (Jam Strobe and Jam Location) LPI Non-cooperative Target Recognition
5. ECCM Capability	⩽ 3 dB Loss in Detection Range in heavy ECM
6. Polarization	Agile transmit, receive/processing
7. Track Computer	Modular architecture-hardware/software
8. Platform	Tracked/Wheeled Armored Vehicles

Table III. Preliminary Environmental Requirements

Condition	Requirement
Temperature Operating (+ Solar Radiation)	-60 to +155°F
Temperature Nonoperating	-70 to +155°F
Relative Humidity	100%
Winds	45 knots – operation 45-60 knots – operation with reduced performance 75 knots – survive, nonoperating
Ice	Normal operation with 1/3 in. thickness
Water Tightness	Spraytight, rain at 5 in./hr and wind velocity at 40 mph
Vibration (Transport Configuration)	5-25 Hz per MIL-STD-167 Type 1
Shock (Transport Configuration)	Drop Tests and Railroad Hump Tests
Setup Time	3 men < 15 min
Time Take Down for Transport	3 men < 5 min

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Section 3

BASELINE SYSTEM DESCRIPTION AND PERFORMANCE

3. BASELINE SYSTEM DESCRIPTION AND PERFORMANCE

3.1 ADVANCED TACTICAL RADAR (ATR) BASELINE CONFIGURATION

A single design multi-mode radar which can be assigned to perform the large volume search, the limited volume multiple track, or both functions is selected as the most feasible approach for the new forward area sensor's baseline configuration.

The baseline configuration selected as most feasible for the new forward area sensor is shown in Figure A. The configuration comprises three self-propelled vehicles, two of which contain identical multi-mode (search, track, identification) Radar Components (RC) each capable of providing surveillance in two 90 degree azimuth sectors (180 degree maximum per RC), while the third vehicle contains the prime power source(s) for the two RC's, a portion of the data/message processing, and the timing and control functions.

The principal functions to be performed by this new forward area sensor include: 1) hemispheric search (through 360° in azimuth and from 0° to 90° in elevation) at the conventional rate in the presence of heavy clutter and ECM; 2) tracking of multiple maneuvering friendly, enemy and neutral targets operating at any altitude over large coverage areas; 3) non-cooperative identification friend, foe, or neutral (IFFN) target classification with further classification as to target type, stores and probable missions if this can be achieved thorugh the use of polarization agile transmissions/processing.

The design approach selected for the multi-mode ATR includes optimum predetection processing, waveform agility, and phased array techniques for time and spatial energy menagement ment. Consequently, the functional survivability of the sensor's baseline configuration selected is high and provides for graceful degradation. In a normal deployment, hemispheric surveillance coverage is provided by two RCs oriented as shown in Figure A, with each RC performing the functions of search, track and identificatin over separate but complementary 180 degree azimuth sectors. This sensor configuration will also accommodate certain constrained deployments (e.g., in Central Europe) where hemispheric coverage from a single site may not be permitted due to terrain. In this situation, by simply reorienting the two RCs and by adjusting the angle between the two antenna faces of each RC, four 90 degree azimuth coverage sectors can be independently directed to obtain the maximum coverage permitted by the terrain. The selected configuration's coverage flexibility also insures a measure of operational survivability by permitting RC deployments on the slopes or at the bases of camouflaging or protective hills rather than on hill crests. If other terrain permits, 360 degrees of azimuthal coverage could be provided by the two RCs, one located on either side of the hill with each RC providing 180 degree surveillance coverage in complementary azimuthal directions to one another.

For those situations where the magnitude of air operations over a particular region demands surveillance and identification of large numbers of targets, sufficient time may not

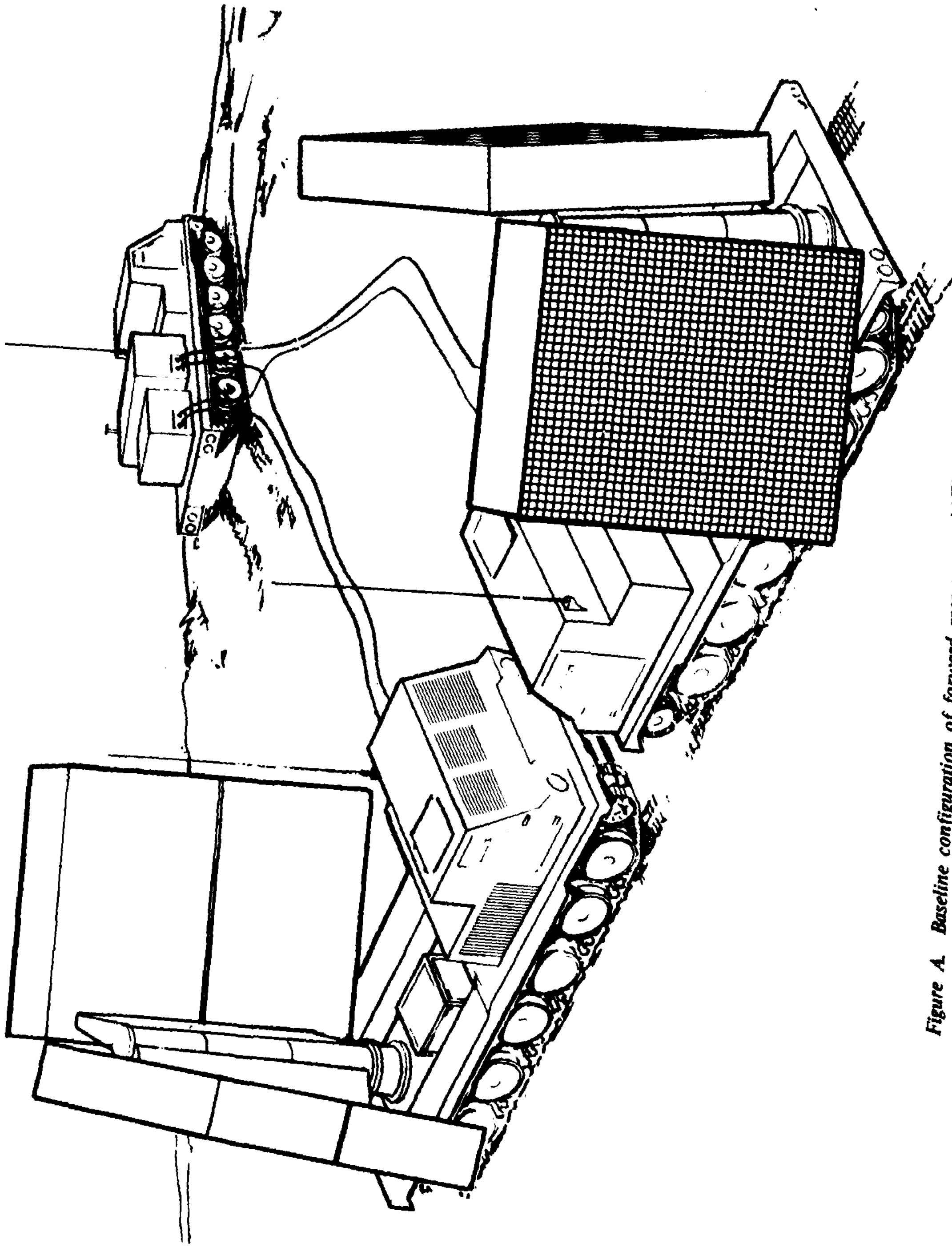

Figure A. Baseline configuration of forward area sensor (ATR)

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be available for the ATR to perform both the search and track functions at the required rates. To accommodate these situations the two RCs and their four antenna faces can be oriented such that their coverages overlap providing increased data rates for selected regions. For example, with proper vehicle and antenna face orientations each of the two RCs could provide: 1) two 90-degree sectors directed such that all four 90-degree sectors of the two RCs overlap one another through 45 degrees; 2) two 90-degree sectors directed such that all four 90-degree sectors of the two RCs overlap one another through 90 degrees (completely). In example 1 above, total azimuthal coverage of 270 degrees can be provided, as shown in Figure B. Additionally, with search (S) and track (T) function assignments as shown in the figure, RC-2 will have its search function halved in the direction of the FEBA and consequently will have more time available to perform the required multiple target track function. Conversely, RC-1 will have its track load halved (assuming uniform distribution of targets) in the direction of the FEBA allowing more time to perform the required search function. To provide a full 360-degree coverage in this situation a third RC (RC-3) could be deployed to provide surveillance coverage in sectors 4 and 8 (i.e., two 45-degree sectors). The search and track functions that RC-3 would be required to perform are half the normal functions (90-degree vs 180-degree); consequently, sufficient time should be available to execute both at the required rates. In example 2 above more time is made available to accommodate surveillance of a still larger number of targets. However, to effect 360 degrees of coverage, two additional radar components (RC-3 and RC-4) would have to be deployed. It is also of interest to note that when two RCs are deployed to provide completely overlapping coverage, as in example 2, one of them could be used as a normal monostatic radar and the other could be used as a bi-static, receive only radar. It should also be noted, however, that such use of the ATRs would do nothing to alleviate the time problem created by heavy target loads.

The effectiveness of utilizing a limited volume outer search fence with a large enclosed volume multiple target tracking capability was considered as another possible way of alleviating the time problem. However, implementation of this type of scan usually implies the utilization of multiple beams per antenna face with the corresponding requirement for multiple receiver/processor channels. Due to constraints associated with the transmitter and polarization agile transmissions/processing a single beam per antenna face has been selected as the most feasible approach.

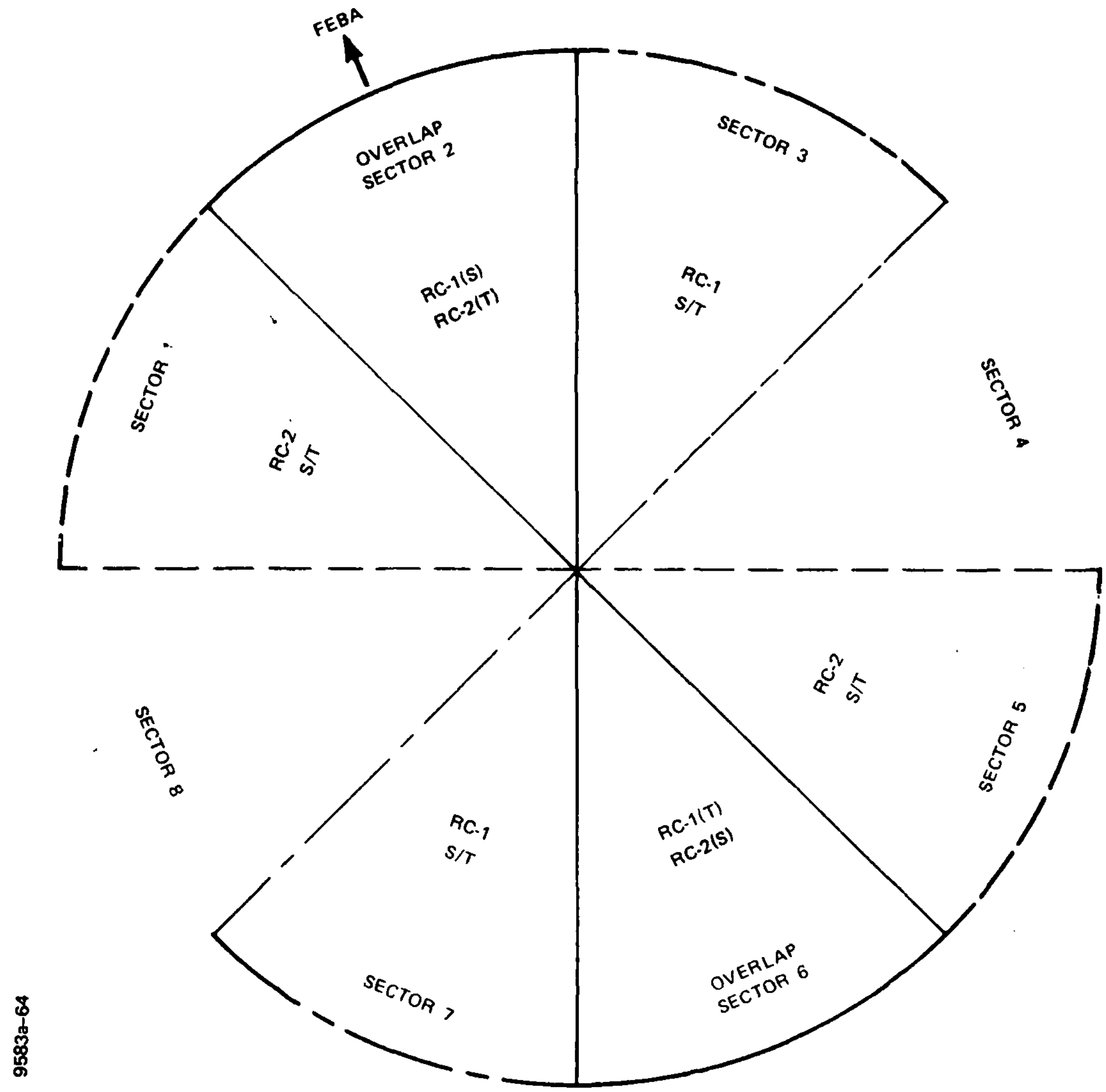


Figure B. 270° of azimuth coverage can be provided through proper orientation of two RCs.

3.2 SELECTION OF OPERATING FREQUENCY

The choice of C-Band as the operating frequency meets the system requirements for the ATR in performing its mission.

For a relatively long range multi-function radar the choice of operating frequency would most likely fall into the LSC or X bands. The individual functions which are combined in one radar as described in the baseline system are:

- Search
- Track
- Threat Assessment

For individual radars which perform a single one of these functions different bands are suggested. Surveillance systems which have as their primary mission detection of targets at long range would favor the lowest operating frequencies. A tracking radar by definition would receive location information from some other sensor and "know where to look". The requirements for tracking would include narrow beam widths for best possible resolution and accuracy on the target location before being further improved by the action of the tracker. Good resolution is also important in discriminating between single and multiple targets so that the tracker can act accordingly. The tracking radar, therefore, would normally employ a higher operating frequency than the search radar. The function of threat assessment, that is, target classification and identification, is performed by producing the best possible image of the target. While range resolution is important it is more easily obtained than angular resolution which is inversely proportional to operating frequency. The threat assessment function, therefore, suggests the highest operating frequency of the three.

While the choice of a single multi-function radar operating in one frequency band does not optimize performance for all the functions, the single radar can be designed to meet the requirements for the ATR mission. It may be shown that three or even two separate radars are not supportable in the rapidly moving battle field environment. Configurational requirements for the future TACS dictate that all TACS elements (both sensors and operations centers) must be highly mobile over all terrain. Tactical mobility is needed to complicate the enemy's reconnaissance, surveillance and targeting problems and thereby enhance system survivability. Two or even three radars performing the ATR function would be at a serious disadvantage in compromising TACS mobility, logistics supportability, and would be ineffective in combining the separate inputs. The single multi-function sensor described later in this report does not possess these disadvantages and can be shown to separately and collectively meet the requirements for the three separate functions.

When one considers the ATR operational requirement for long-range surveillance in a high density clutter environment (chaff, rain, ground), the basic operating frequency bands that should be considered are the S- and C-Bands. Lower frequency band radars would be too large to comply simultaneously with the requirement for resolution and tactical mobility, while higher frequency band radars would not be able to provide the required long-range surveillance in clutter, especially rain. Some general considerations for selection of operating frequency are given in Table 1.

Table I. Basic Consideration in Frequency Selection

Higher Frequency	Lower Frequency
Better Resolution	MTI More Effective
Angular	Less Sensitive to Precipitation
Doppler	Greater Size and Weight for same Resolution
Superior Accuracy	Limited Absolute Bandwidth
Chaff Backscatter Lower	
Low Altitude Detection Easier	
Multipath Resistant	

C-Band is preferred over S-Band due to the greater angular resolution provided by the mobility-constrained ATR antenna aperture. Greater angular resolution is advantageous in detecting the existence of closely spaced targets, assisting in the identification of non-cooperative aircraft/missiles, and in the detection of non-jamming targets being accompanied by escort screening jammers. S-Band designs will have, in general, lower transmission losses and hence can operate with reduced power aperture products.

The choice of C-Band was made with mobility as an absolute constraint. The requirements for transportability in various military aircraft, also mobility in the US and foreign countries, dictate requirements that are severe in terms of physical envelope and ease of deployment. After the four faced phased array configuration was selected the decision had to be made as to the deployment of each face on available vehicles. It was decided that a single face per vehicle, necessitating 5 vehicles for the ATR, would be unattractive. The baseline configuration with two faces per vehicle imposes dimensional requirements on the aperture. After studying the ATR mission and deriving system requirements it is felt that these aperture sizes represent the minimum performance parameters that can be allowed. In other words, the resolution and accuracy afforded by a C-band system with these antenna sizes is at the limit of the system parameters. An S-band system with the same physical configuration would suffer from affording worse resolution and accuracy capability.

A preliminary comparison between S and C-Band radars has been made and the results are summarized in Table II. The major differences between the two radars are.

a) The S-Band radar requires 5 vehicles while the C-Band requires only 3 vehicles, a most important characteristic when considering battlefield usage.

b) The C-Band radar becomes range limited due to attenuation at a rain rate of approximately 4 mm Hr over 25 percent of the path.

It does not appear likely that the S-Band radar can be decreased in size without significantly affecting performance with respect to maximum range, height accuracy and performance in an ECM environment. On the other hand, the C-Band radar may be able to be deployed in a more favorable location (due to its smaller size) thereby somewhat decreasing its maximum range requirement.

Many other factors must be considered before one can recommend one band over the other, but it appears that the C-Band radar may be able to offer several operational advantages. Other factors which may favor S-Band relate to the state-of-the-art of solid state microwave power generation at C-Band which is not as far advanced as at S-Band. Since the S-Band technology status is better known, the efforts in this study were directed at C-Band in order to provide a more accurate basis for final recommendation between the two bands. A more comprehensive comparison will be made between S- and C-Band as a result of the S-Band tactical antenna study currently in progress at ITT Gilfillan.

Table II. Comparison Table for C-Band & S-Band Radars

	Clear Weather		Rain (4 MM/HR)		Favored Band	
	S	C	S	C	S	C
* ● Required Number of Vehicles	5	3	5	3		√
* ● Range Margin at						
175 Miles	0 dB	0 dB	-0.06 dB	-1.92 dB	√	
100 Miles	2.9 dB	2.87 dB	2.86 dB	1.77 dB	√	
● Required Transmitter Power	0 dB	1.57 dB	0 dB	1.57 dB	√	
● Two Way Antenna Gain	0 dB	0 dB	0 dB	0 dB		
● Height Accuracy						
175 Miles	3.38 kft	2.54 kft	3.39 kft	2.77 kft		√
100 Miles	1.62 kft	1 kft	1.63 kft	1.08 kft		√
* ● Required Noise Jammer Power for Equal J/S Ratio	0 dB	4.26 dB	0.35 dB	5.36 dB		√
● Chaff Backscatter to Target Ratio	3.86 dB	0 dB	3.86 dB	0 dB		√
Arm Signature	-0.2 dB	0 dB	0.037 dB	-0.55 dB		
Elint Receiver Signature	-0.4 dB	0 dB	-0.75 dB	-1.1 dB		

Notes:

1) Symbol * indicates significant performance difference
2) Design based on: A) Equal clear weather range performance at 175 miles
   B) Equal antenna gain (dBI)
   C) Equal search time
   D) 10% duty factor
3) Rain extent assumed over 25% of path length
4) Assume chaff weight is constant

3.3 SUMMARY DESCRIPTION

The primary output of the ATR is a summary of all target tracks within the local surveillance volume which are also available for centralized operation center usage.

The baseline radar design includes the following subsystems:

- Four Polarization Agile Antenna Arrays with Distributed Solid State Transmitter and Independent Polarization Agile Receivers
- Four Signal and Data Processors (one for each Antenna Array)
- One Data/Message Processor, Timing and Control and Synthesizer Unit
- One Display
- One Primary Power Supply
- 60° to 90° ARM Alarm Sensor (Top Coverage)
- Three vehicles

The antenna vehicles (two per radar) each carry two antenna faces providing a total of 180° azimuth coverage. Each antenna vehicle also carries the two corresponding signal and data processors. The third vehicle carries the display (cab mounted), the primary power supply, the data message processor, the timing and control, and the synthesizer unit.

Each antenna face covers a 90 degree azimuth sector the center of which is adjustable mechanically. The basic elevation search coverage is up to 20 degrees with additional coverage to 60 degrees for Track and ARM Alarm. 60 to 90 degree coverage for ARM Alarm is achieved with a separate antenna and equipment.

Each face operates with a single electronically steered beam which can be independently coded. It is desirable to transmit from local faces simultaneously to reduce the possibility of mutual interference. Each beam can also be steered to provide random access coverage of the surveillance volume.

During a search frame period (approximately 8 seconds with no fine target tracks) all detected targets within the search volume can be tracked. If higher data rates or increased accuracy is desired then selected targets can be tracked in a fine angle measurement or burn thru mode. 61 targets per 10 seconds per antenna face can be measured in this mode while maintaining a basic search period of 10 seconds. This corresponds to an average of 25 targets per ATR at a 2 second rate.

The large antenna aperture (12 feet wide by 13.3 feet high) provides a high degree of angular resolution (1.16° az by 1.05° el) and accuracy. Additionally the large aperture permits the range and data rate requirements to be achieved with a total average transmitter power of 20 Kilowatts.

A simplified block diagram of the baseline design is presented in the Figure. The diagram basically includes the equipment for one face plus that located on the prime power carrying vehicle.

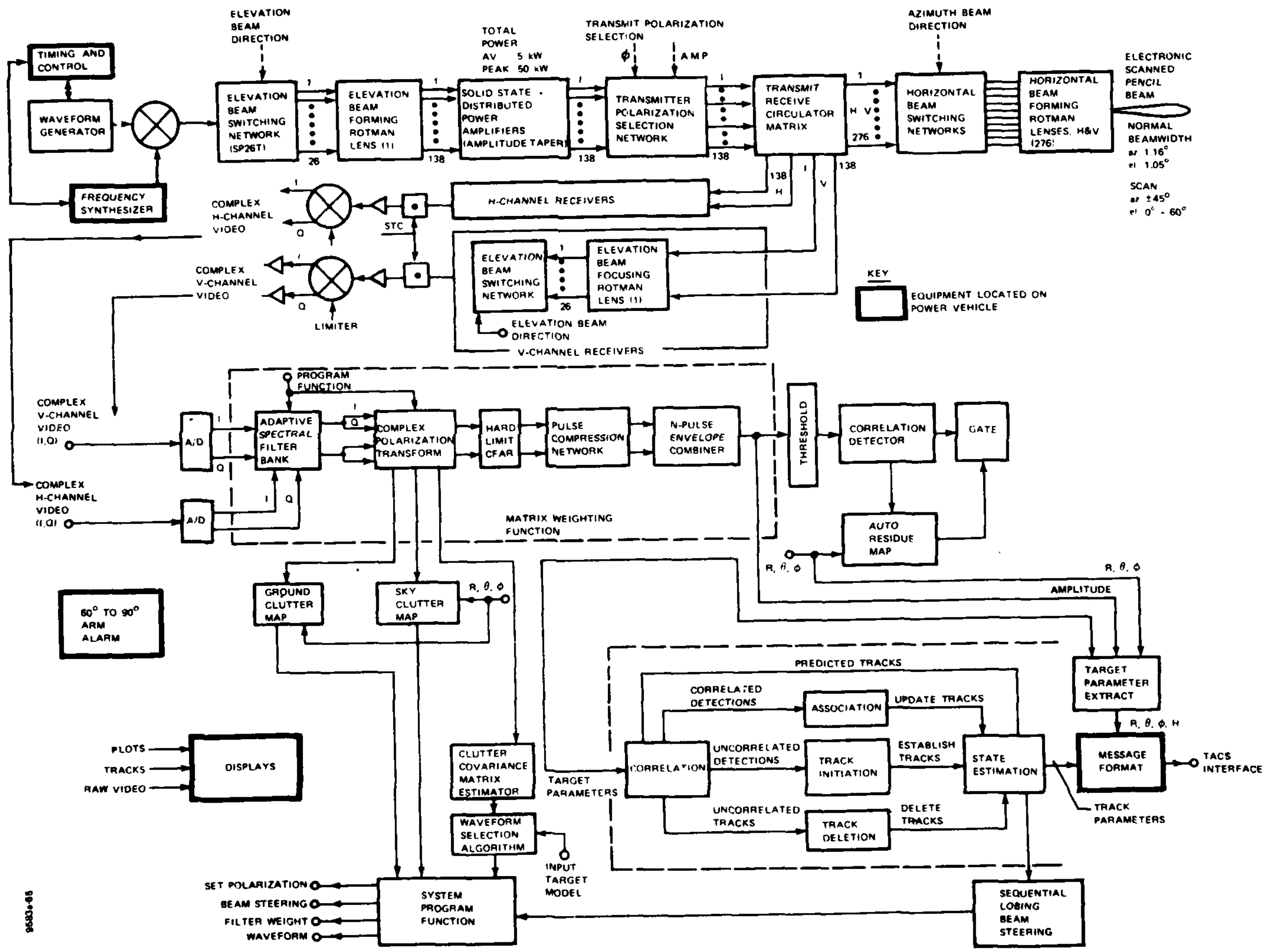
Search Mode

Referring to Figure A, an independently coded waveform is transmitted simultaneously by each of the four antenna faces in beam directions selected by the corresponding elevation and azimuth beam switching networks. The coded waveform will normally be a phase coded pulse with a duration of 277 microseconds and a coded bit width of 75 nanoseconds. A constant pulse repetition period of 2.77 milliseconds is normally employed resulting in a waveform duty factor of 0.1. Higher pulse rates (up to 4 or 8 times the nominal pulse repetition rate) can be selected to obtain improved performance in rain, chaff, ground clutter, or to improve doppler resolution. The higher pulse rates are transmitted at the same waveform duty factor of 0.1 since the distributed solid state amplifier is peak and average power limited. Thus the higher pulse rates will be transmitted with correspondingly shorter pulse widths and respectively lower correlation gains (fewer bits per pulse).

The basic search volume is from 0 to 20 degrees in elevation and 360 degrees in azimuth. This volume is nominally searched in 8 seconds with each array face covering a 90 degree azimuth sector. Each array face can also be programmed to track up to 60 degrees in elevation primarily for the purpose of maintaining surveillance against ARM threats which have penetrated the basic search volume. At elevation angles between 60 and 90 degrees elevation ARM surveillance is achieved by a separate ARM Alarm sensor. It is anticipated that the design of this sensor would be derived from the current Air Force ARM Alarm program and would be an all solid state range rate radar operating in the UHF region. It is estimated that an average transmitter power of less than 1 kilowatt would be adequate to obtain the desired performance with an effective antenna area of approximately 1 square meter. No new technology is anticipated in implementing this sensor.

The transmitted beam from each face is optimally polarized via the transmitter polarization network. An independent and optimum receiver polarization value can also be selected. This versatility is expected to provide significant improvement in performance in rain, chaff, against ARMs and in the reduction of stand-off-jamming interference. It is also expected to aid significantly in the potential non-cooperative identification of targets.

The antenna beamwidth (transmit and receive) normal to each array face is 1.16 degrees in azimuth by 1.05 degrees in elevation. The beamwidth widens as the inverse cosine of the scan angle due to the geometric reduction of the effective aperture. The total available effective aperture is utilized for scan over the full azimuth angle and up to 5.5 degrees in elevation. Constant probability of detection is maintained over this search volume by adjusting the number of hits per beam direction between values of 1 and 6. The lower elevation beam angles will normally require multiple hits due to higher atmospheric losses and MTI implementation for reduction of ground clutter. At elevation scan angles between 5.5 and 20 degrees the elevation beamwidth is increased to allow for approximately 1 hit



Mid-performance baseline system block diagram (one antenna face)

while maintaining a constant probability of detection at 45 degrees azimuth in accordance with the required range/elevation coverage contour.

Extremely low transmit antenna sidelobes are achieved by utilizing a heavy amplitude taper in the distributed solid state transmitter and the elevation and horizontal Rotman lenses. The low receiver sidelobes are obtained by amplitude taper in the receiver Rotman lenses. The transmit/receive tapers (>30 dB) result in sidelobes which are down >50 dB in the azimuth and intercardinal plane and >30 dB in the elevation cardinal plane. This low sidelobe level provides significant performance improvement with respect to intercept probability, jamming susceptibility and ARM vulnerability.

In the search mode each detected target is measured and catalogued with respect to range and angle. The range resolution is approximately 38 feet and range accuracies comparable to this value or better can be obtained if desired. The coarse angle measurement is made in the search mode by recording the target return amplitude at each beam position in the vicinity of the target. The two orthogonal optimum sets of beam measurements can then be used to estimate the true target direction. The optimum set can be selected based upon signal level. Alternatively all amplitude measurements in the vicinity of the target can be used, with proper weighting, for the angle measurement. This would result in slightly improved accuracy since additional and independent data would be applied to the angle estimation.

The search mode thus provides a track-while-scan capability for all detected targets within the basic search volume at a data sampling rate of 8 seconds (the search frame time). These target tracks would be available locally for transmission to a centralized operation center via a communication link.

High Data Rate/Fine Angular Measurement Track Mode

In a high target density environment the 8 second data rate will be inadequate to properly associate crossing or near crossing target tracks. This association is required in order to maintain an accurate threat assessment and prevent target identification confusion. Higher data rates will also be required for selected high priority targets. In addition, friendly interceptor vectoring, one of the major functions of the ATR, can be accomplished in a shorter time with improved height data. This is because end game altitude changes will in general be time consuming. It may be concluded that under certain conditions that a higher data rate and an improved angle measurement accuracy would result in significantly improved performance. The baseline design can operate at appreciably higher data rates by virtue of its electronic random access beam direction selection. Since the basic frame time is 8 seconds and the maximum allowed frame time is 10 seconds, there is a 2 second residue which can be used for fine angle measurement and tracking of high priority targets. On the average a fine angle measurement can be made on 61 targets in this 2 second period while maintaining an

overall search period of 10 seconds. Since these numbers apply to one antenna face the ATR is capable of fine tracking 244 targets (four faces) in a 10 second period while maintaining the basic volume search frame time of 10 seconds. Since the available 2 second margin can be distributed throughout the 10 second frame time as desired, then higher track data rates can be achieved if fewer targets are tracked. The number of targets that can be fine tracked at various data rates while maintaining a 10 second search frame time is illustrated in the table following.

Track Data Rate Capability

Quantity of Targets that can be Fine Tracked	Track Data Rate	Search Data Rate
244	10 sec	10 sec
122	5 sec	10 sec
61	2.5 sec	10 sec
24	0.975 sec	10 sec

The optimum sequential lobing angular accuracy would be obtained when a target is located midway between the beams used for the angle measurement (i.e., at beam crossover). Since the beams have fixed directions the target will in general not be located at this optimum position. This is true in botn the search and the fine angle measurement mode. The increased angle accuracy is, however, achieved in the fine angle measurement mode by providing increased beam position resolution (a factor of two) in the azimuth direction.

This increased resolution allows the beams to be selected so that the target is closer to the optimum crossover position.

Other Modes

In addition to the modes described above the ATR can operate adaptively to enhance performance in chaff, rain, jamming, clutter or ARM threat environment. Protection against the ARM threat by utilization of an advanced decoy design is currently being studied by ITT Gilfillan under separate contract. Adaptive measures include the following techniques:

- Higher pulse rates to enhance doppler resolution.
- Polarization agility to enhance target return and/or to reduce clutter back scatter. May also be used for target identification.
- Pulse-to-pulse frequency agility.
- Instantaneous wideband transmission to aid in target identification.
- Pulse width agility. Short pulses may be used for rapid short range surveillance or to reduce range sidelobe interference in a dense target environment.
- Code agility.

- Long dwell time capability to "burn-thru" high priority directions if desired.
- Coherent netting for potential use in passive correllation location of radiating sources. This is an inherent capability of the phased array approach which can be effected by adding equipment for many simultaneous receiver beams.
- Operation in a hostile environment is treated in detail in Section 4 of this report.

3.4 BASELINE PERFORMANCE

3.4.1 SYSTEM PARAMETERS AND OVERALL PERFORMANCE (BENIGN ENVIRONMENT)

The baseline system has been designed to allow it to operate in a benign environment while still being able to efficiently contend with the hostile TACS environment.

The pertinent system parameters and performance was initially determined in a benign environment. The system design, of course, includes many sophisticated and advanced techniques which are necessary to effectively contend with the predicted hostile environment. In most cases the inclusion of these techniques does not affect operation in a benign environment and often are adaptive and, therefore, only used as needed. Several of the included techniques, however, have a major influence on the system performance. The most notable of these are the low sidelobe design and the utilization of polarization agility. The low sidelobe design reduces the antenna effective aperture by as much as 6.4 dB. Additional line losses are also incurred due to the low sidelobe design and the incorporation of polarization agility. These additional losses amount to approximately 3 dB. The total penalty paid is, therefore, on the order of 10 dB of additional power aperture product required in order to maintain the same performance in a benign environment that would be obtained with a uniform aperture amplitude taper and a non-agile polarization capability. Although the cost of these techniques is high (both in dB and $), they are deemed quite necessary in order to maintain operational and functional survivability in a hostile environment.

The major parameters and system performance are presented in the Table 1.

Table I. Buseline System Parameters and Performance

Parameter	Value	Comments
Frequency Band	5.3 to 5.9 gigahertz	Potentially available band
Antenna aperture size	12 ft wide by 13.3 ft high	Maximum size for mobility
Number of antenna faces per radar	4	4 faces required to achieve 360° azimuth coverage. 3 faces resulted in excessive aperture loss at wide scan angles
Basic coverage	0 to 20° elevation 360° azimuth (can scan to 60° elevation as required)	Basic coverage obtained from advanced tactical antenna requirements
Auxiliary coverage	Hemispherical to zenith (60° to 90° elevation)	Zenith coverage for ARM alarm obtained with separate UHF solid state sensor
Search time for basic coverage (no fine track)	7.97 seconds	Computed. Coarse angle measurement obtained in search
Scan technique	Electronic switching	Efficient random access increases track capability
Beam-forming technique	Rotman lenses	Effective, small and relatively inexpensive
Transmitter type	Solid state, distributed	Graceful degradation, low loss
Average power per face	5 kilowatts	Anticipated maximum based upon primary power and solid state considerations. Power is referred to transmitter output
Peak power per face	50 kilowatts	
Number of beams per face	One	Provides adequate number of hits for low angle MTI and minimizes number of required parallel receivers. Moderate integration loss
Number of search hits per beam direction	One to six (function of az, el angle)	
Pulse repetition frequency	360.8 Hertz (PRP = 2.772 milliseconds)	Unambiguous instrumented range of 200 nautical miles
Pulsewidth	277.2 microseconds or less	Improves LPI characteristics and processing gain. Compatible with solid state transmitter
Search bit width	75 nanoseconds (37.5 feet)	Selection to match bit width to target size (i.e., target range extent) and provide adequate processing gain in rain and chaff
Basic range coverage (P_D = 0.5, P_{FA} = 10^{-6})	50 miles, 20° el 175 miles, 0° el to 5.5° el	Requirement taken from tactical antenna specification

Table I. Baseline System Parameters and Performance (Continued)

Parameter	Value	Comments
Intercardinal and azimuth cardinal sidelobes	<−50 dB	
Elevation cardinal sidelobes	<−30 dB	
Average number of fine target tracks per 10 seconds per face (assumes targets are uniformly distributed at range of 175 miles over 0 to 5.5° elevation and ±45° azimuth)	61 (244 per radar)	Computed. 24 targets can be fine tracked at better than a 1 second data rate
Maximum 2-way antenna gain (directivity)	>86 dB	Consistent with sidelobe level and antenna size
Beam shape loss	1.43 dB	
Area loss due to amplitude weighting	6.4 dB	Estimated losses
Transmitter line loss	3.2 dB	
Receiver line loss	3 dB	
Receiver noise figure	3 dB	
s/n processing margin	3 dB	Margin to be obtained over outer range contour
Multiple hit integration	Noncoherent	Arbitrary conservative assumption
Target area	3 square meters	Target characteristics taken from tactical antenna requirements
Target model	Swerling I	
Angle measurement technique	Amplitude comparison with sequential lobing	Good accuracy in small time
Search beam step size	0.5° beamwidth in az 0.433° beamwidth in el	Compromise between volume coverage and total search scan time
Track beam step size	0.25° az, 0.433° el	Compromise between track accuracy and equipment complexity
Track height accuracy at 100 miles up to 5.5° elevation	500 feet rms for one fine track measurement	Nonfluctuating target

3.4.2 SYSTEM PERFORMANCE (ECM AND CLUTTER)

The baseline system design was initially achieved assuming a benign environment.

Having met the system requirements without ECM or clutter it was then necessary to include the required techniques to obtain adequate performance in a realistic hostile environment. This subject is treated in detail in the following section.

A summary of the system performance in clutter, rain, chaff and a jamming environment is given in Table II.

TABLE II

System Performance Summary (ECM and Clutter)

Environment	Level	Technique	Radar Range
Ground Clutter	Conventional	3 Pulse Canceller	175 nmi
Rain	4mm/hr	8 Point FFT and Circular Polarization	150 nmi
Chaff (and folded ground clutter)	$10^{-7} m^2/m^3$	Four Times PRF (1600 Hz) Optimum Transmit/Receive Polarization, Near Optimum Bimodal Filter with 8 Pulse Sequence	150 nmi
Barrage Stand-Off Jammer	19 kW/MHz	None Special	82.5 nmi (i.e. 3dB reduced from benign)

3.4.3 ANGLE MEASUREMENT ACCURACY

A coarse and fine angle measurement capability has been included in the baseline design.

The coarse angle measurement is made as part of the normal search scan and therefore does not add to the search frame time. In the fine angle measurement mode the beam positioning resolution is improved by a factor of two in the azimuth plane which results in an improved measurement accuracy in both the azimuth and elevation target angles. The coarse (search) and fine (track) angle accuracies have been computed based upon the following simplifying and constraining assumptions:

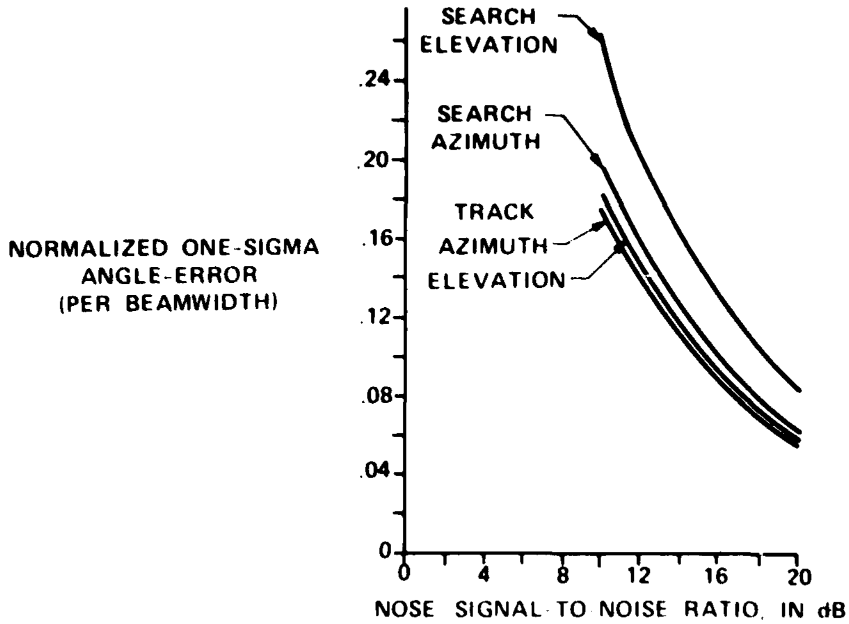
- Only system noise will degrade the angle measurement (i.e. target signal return is non-fluctuating during the angle measurement)
- Sequential amplitude comparison is used for making the angle measurement estimate
- The antenna pattern is known perfectly for all beam positions
- All system bias errors are zero
- System noise amplitudes are assumed small enough so that a linear angle error transfer function can be used
- The target has a uniform probability distribution in angular location

Although the angle accuracies computed are adequate for a comparison between coarse and fine angle measurement they indicate the ideal angle accuracy for the radar. In practice the single measurement angle accuracy will be degraded. It should be noted, however, that tracking (scan-to-scan) and increased dwell time will improve the target angular estimate.

The angular accuracy results are presented in Figures A, B and C.

In Figure A the two sets of curves refer to the angular accuracies that would be obtained in the search mode and the fine track mode. In the search mode all detected targets can also be measured in angle without affecting the frame time. A target detected with a 16 dB signal-to-noise ratio (referred to beam center or nose of beam), would be measured with an angular accuracy of 0.135 beamwidth in elevation and 0.1 beamwidth in azimuth. These numbers can be converted to degrees or feet knowing the respective beamwidths and target range. Similarly the fine track angular accuracies on the same target would be approximately 0.08 beamwidth in elevation and azimuth.

As the target range is reduced the target location error is reduced by the geometry as well as the improved signal-to-noise ratio. Figure B presents target height errors estimated for targets at 100 and 175 miles using the high resolution fine track mode. A threshold target ($\approx$13 dB) detected at 175 miles would be measured in height to an accuracy of approximately 2700 feet. At 100 miles the signal-to-noise ratio would be improved by approximately 10 dB and the corresponding height error would be near 500 feet.



NOTES:

1	SEARCH STEP SIZES	.5 AZ BW .433 EL BW
2	FINE-TRACK STEP SIZES	.25 AZ BW .433 EL BW

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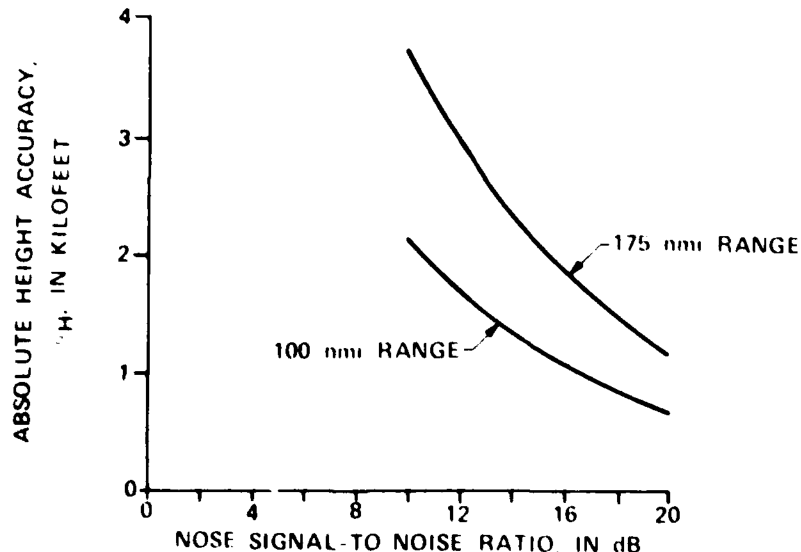
Figure A. Comparison of coarse (search) and fine (track) angle accuracy



NOTES:

1	AZIMUTH BEAM STEP RESOLUTION	.25 BEAMWIDTH
2	ELEVATION BEAM STEP RESOLUTION	.433 BEAMWIDTH

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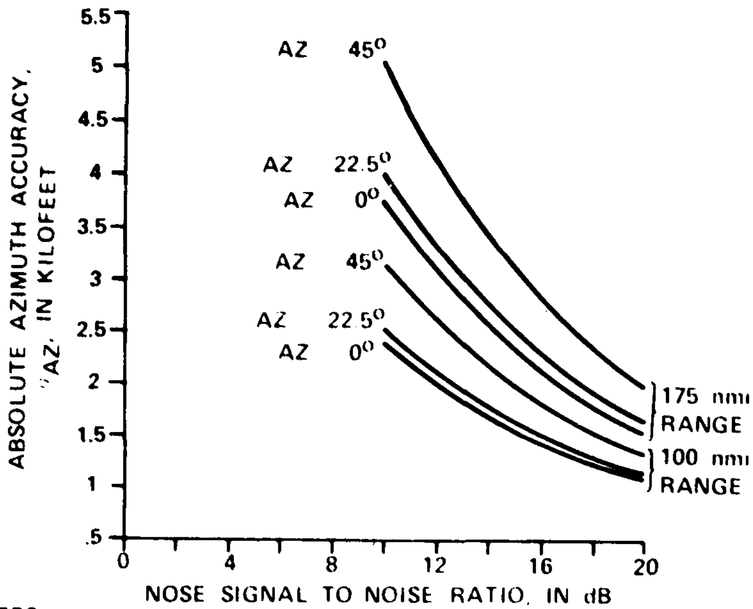
Figure B. Fine (track) height accuracy vs signal-to-noise ratio

In azimuth the beamwidth changes with scan angle and Figure C presents azimuth location errors in kilofeet at various scan angles and two ranges.



NOTES:

1 AZIMUTH BEAM STEP RESOLUTION .25 BEAMWIDTH

2 ELEVATION BEAM STEP RESOLUTION .433 BEAMWIDTH

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Figure C. Fine (track) azimuth accuracy vs signal-to-noise ratio

3.4.4 RADAR SIGNATURES

The baseline radar design will generate various signatures which include: Visible, Infra-red (IR), Radio Frequency (RF).

The non-camouflaged visible (daytime) signature of the radar will be easily detected by airbourne sensors. It is estimated that angular resolutions on the order of 5 micro-radians can be achieved by surveillance cameras. At satellite and surveillance aircraft altitudes this resolution corresponds to distances at the radar of between a few feet and several inches. The radar design is readily adapted to visible camouflage since fixed, non-rotating antennas are used. Relatively simple camouflage techniques should be capable of protecting the radar from visible surveillance detection. Similarly, the radar camoufl..e should be able to provide the required protection against missile threats using guidance sensors in the visible spectrum.

The IR and RF signatures are more difficult to disguise or attenuate. IR sensors are estimated to have sensitivities capable of detecting temperature differentials in the order of 1 degree centigrade. Normal surrounding vegetation and ground IR radiation variations will most likely prevent missile sensors from utilizing this high sensitivity. The IR sensor sensitivity will be less than the theoretically possible in order to contain the potential number of false alarms to a managable level. One might expect temperature rises of 5° to 15°C, for example, to be a reasonable upper limit for the IR signature of the ATR.

Losses within the antenna array will cause temperature rises far in excess of this value. It is expected that hot spots could approach rises exceeding 50° and widespread temperature rises might be in the order of 25°C or more. Cooling of the array may prove difficult without incurring additional RF losses and or weight.

Overhead camouflage will probably be adequate, as in the case of the visible signature, to hide the radar from high altitude surveillance aircraft and or satellites. The major difficulty is that of missiles with IR sensors. It is anticipated that some combination of array cooling, camouflage and decoys may be required in order to afford the ATR adequate survivability protection.

The RF signature of the radar is determined by the antenna pattern, the waveform and the transmitter power. Even with wideband LPI techniques the ATR radar will easily be detected by future surveillance receivers located in the radar main beam. More pertinent is the sidelobe radiation since this radiation is available on a continuous basis providing higher data rates to enemy sensors or receivers.

The effective radiated peak power in the sidelobes of the ATR is given approximately as:

$$\text{Effective Radiated Power} = \overline{ERP}$$

$$\overline{ERP} = \frac{P_T \; G \; L \; \overline{SLF}}{4\pi R^2} \text{ Watts/m}^2$$

Where:

P_T = Transmitter peak power in watts

G = Directive gain in radar main beam

L = Total system loss factor including transmitter line losses and atmospheric losses

$\overline{SLF}$ = Sidelobe loss factor

R = Range to radar in meters

Typical values for these parameters are:

P_T = 50,000

G = 30,000

L = 0.16 → 8 dB

$\overline{SLF}$ = 10^{-3} to 10^{-5} ≈ -30 to -50 dB sidelobes

then:

$$\overline{ERP} = \frac{20 \text{ kW/m}^2}{R^2} \quad \text{for } -30 \text{ dB sidelobes}$$

$$\overline{ERP} = \frac{0.2 \text{ kW/m}^2}{R^2} \quad \text{for } -50 \text{ dB sidelobes}$$

These are numbers computed for one array face. Since simultaneous array transmissions are utilized these numbers can be 4 times higher for the ATR.

The polarization signature will vary depending on the effectiveness of polarization agility. Similarly the pulse width can vary at least between the value of 277 microseconds and 30 microseconds. The nominal instantaneous bandwidth is 15 MHz and will be centered within the 5.3 to 5.9 GHz band. Pulse-to-pulse frequency agility can be implemented.

In the wideband mode (potentially used for target identification), the instantaneous bandwidth may be as great as 200 to 300 MHz. Average power densities will be approximately one tenth of the estimated peak values since a constant 10 percent duty factor is envisaged.

3.4.5 DETECTION OF SMALL TARGETS

The ATR with its high power aperture product and electronic beam switching will provide a superior small target detection capability in comparison to other sensors.

Within the basic search volume, 3 m^2 targets can be detected with a 50 percent probability along the outer range contour. This contour is at 175 miles range for elevation angles up to 5.5 degrees and decreases to a range of 50 miles at 20 degrees elevation. Smaller targets can also be detected by the ATR but at reduced ranges. Listed below are approximate detection ranges for various target sizes at elevation angles of 5.5 degrees or less and 20 degrees elevation angle:

Target Size (m^2)	Detection Range at Elevation Angles Smaller than 5.5° (nmi)	Detection Range at 20° Elevation (nmi)
10	230	56
1	130	31
.1	73	17
.01	41	12

Unless special precautions are taken, the small target detection capability of the ATR is such that small, high speed targets might penetrate the basic search volume without detection, and enter the conical volume extending above the radar at elevation angles greater than 20 degrees. For this to occur in the normal scan mode, target velocities of several thousand feet per second would be required in conjunction with target altitude capabilities exceeding 20,000 to 45,000 feet. In essence the search radar puts up a detection fence at a periodic rate equal to the search frame time (8 to 10 seconds). High altitude, high speed targets might fly over this fence or pass through the high altitude portion of the volume in between normal search scans. A partial solution to this problem is to increase the fence altitude beyond the target altitude capability. This can easily be accomplished by providing a high gain beam at an elevation angle in the vicinity of 20 to 60 degrees. Normal search beams at these elevation angles are increased in elevation beamwidth to approximately 13 degrees in order to maintain the 3 square meter target detection capability along the required range contour. By providing the high gain beam the small target detection capability is extended to altitudes beyond 125,000 feet at the selected elevation angle. The additional scan time to provide this small target fence is approximately 0.4 seconds. This number is derived from the product of the number of azimuth beam positions (138) and the dwell time per position for a single hit (2.77×10^{-3} seconds).

The major deleterious effect is to decrease the available fine track time from 2 seconds to approximately 1.6 seconds. This represents a target track data reduction of

approximately 20 percent. The solution is still only partial with respect to the detection of small targets since high velocity targets could still pass through the fence search volume between scans. For example, a missile with a velocity of 3,000 feet per second can travel approximately 5 miles in the 10 second scan time. The fence "thickness" normal to the missile trajectory could be approximately 2 degrees for the high gain beam. This 2 degrees thickness corresponds to a distance of 0.8 miles at a range of 20 miles. Under these conditions the very small high velocity missile would have a relatively high probability of successfully penetrating the fence without being detected. The detection of small targets can be enhanced by employing additional antenna arrays to improve search rates in selected high priority directions. The radar faces cover 90 degree sectors and can be "ganged" to provide overlap if desired. Further improvement can also be gained by "erecting" the missile fence more often thus sacrificing additional available track time. The sampling rate can be doubled (i.e., a missile fence every 5 seconds rather than every 10 seconds) by sacrificing an additional 0.4 seconds of available track time. The available track time would be reduced now to approximately 1.2 second.

In addition to the above techniques it will be extremely important to address the "false" target probability associated with small target detection. Dramatic increases in undesired target numbers are realized as the target detection threshold area is reduced. It is anticipated that high pulse repetition rates will be needed in this mode to provide increased doppler discrimination against undesired targets. The implications associated with the reliable detection of small targets can have major impacts on the system design. Additional improvement with respect to increased power or aperture appears undesirable from a mobility and prime power point of view. As indicated above, the ATR deployment can increase the effective power aperture product but even this approach is somewhat limited since overlapping coverage quickly results in a prohibitive increase in the number of array faces. Also requirements may be significantly affected, depending upon weapon and fire control capability. In essence, however, the ATR with its high power-aperture product and electric beam switching will in general provide a superior small target detection capability when compared with other sensors.

Assuming that the desired small targets will be detected at elevation angles up to 20 degrees, then target tracking is provided by the array faces for elevation angles between 20 degrees and 60 degrees. Targets in this volume are monitored for range and range rate only but narrow beams are provided to reduce the undesired target detection problem while providing adequate sensitivity. Beyond 60 degrees elevation (i.e., 60 degrees to zenith) the ARM Alarm sensor currently being developed by the Air Force is recommended. This UHF solid state sensor provides quadrant angle information and range and range rate data. Signals would be used to indicate a missile attack. For such a condition any number of preventive measures could be implemented including decoy activation, radar shutdown weapon dispatching, etc.

3.5 SYSTEM SYNTHESIS

3.5.1 PRELIMINARY ASSUMPTIONS

The system was synthesized to achieve operational performance relative to the ATR requirements.

Several preliminary assumptions were made representing design choices which limit certain parameter values. These choices were not made to limit the design but to make clear that beyond these values the design may become difficult to achieve from a practical point of view. These initial limiting constraints are listed as follows:

- Maximum average RF Power at Solid State Transmitter — 20 Kilowatts

  (Based upon a reasonable number of transmitter modules, required prime power and reliability).

- Maximum Antenna Size — 11 feet high, 7 feet wide

  This assumption was based upon the largest antenna size that would be mobile. This was increased to 13.3 feet high and 12 feet wide and mobility was still obtained. The increase in aperture size was necessary to include polarization agility and low azimuth sidelobes).

- Six search hits when beam is looking in direction resulting in lowest signal return (0 degree elevation and 45 degrees azimuth).

  (Fewer hits would result in poor MTI and greater would increase integration losses).

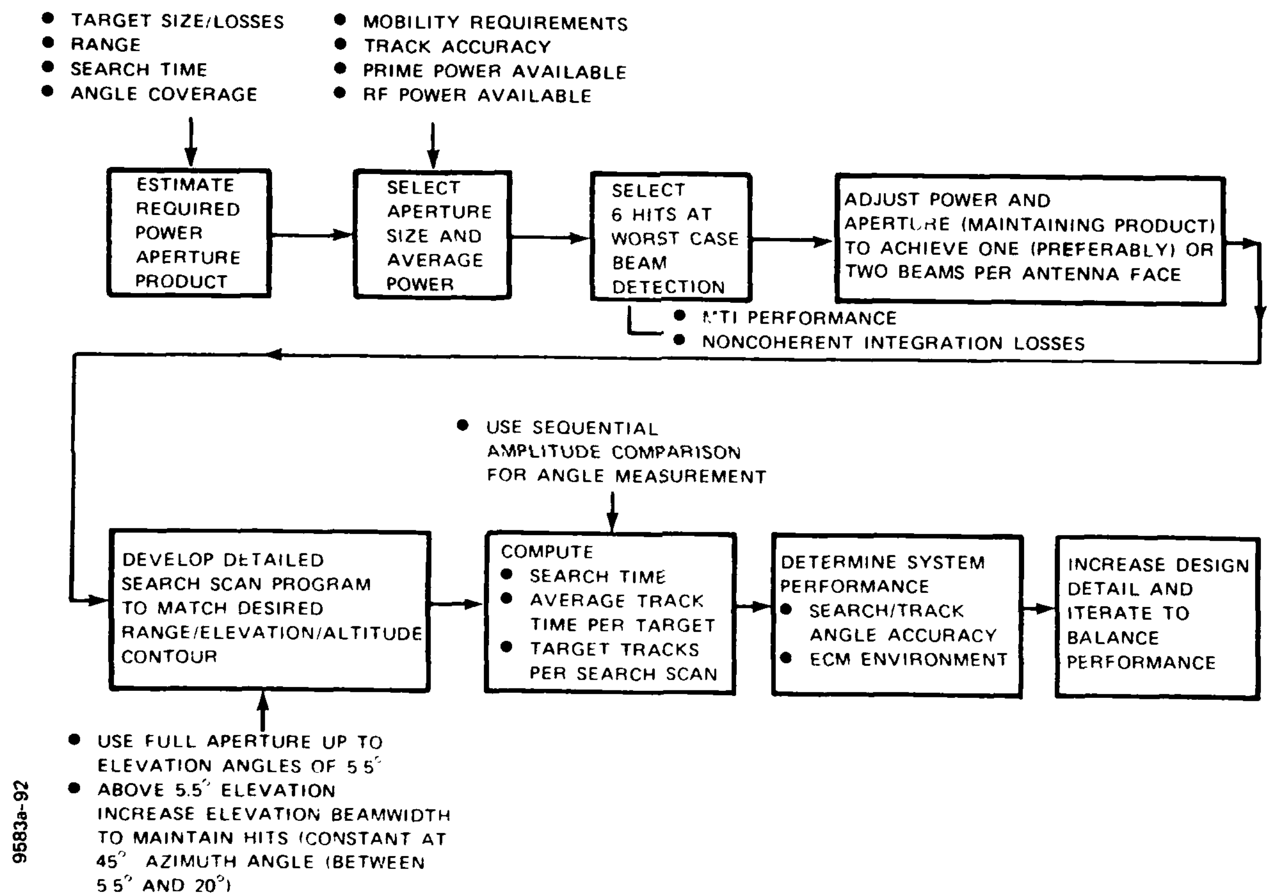
- 10 percent waveform duty factor.

  (To achieve maximum practical LPI, high time-bandwidth product and poor rise time to increase multipath effect on ARM.

Figure A illustrates the basic sequence that was followed in developing the system design and performance characteristics.

A preliminary system design and performance analysis indicated that near maximum aperture and average power values would be required in order to achieve the volume search coverage within the required scan time (less than 10 seconds with no fine target tracking).

With the selected values of power aperture product and utilization of 6 hits for detection a scan program was developed based upon one simultaneous receive beam per antenna face (4 per radar for 360 degrees coverage). At elevation angles below 5.5 degrees the hits per beam position were varied to maintain a minimum 0.5 probability of detection. Above this angle and up to 20 degrees the elevation beamwidth was increased to maintain 0.5 probability of detection with 2 hits at 45 degrees azimuth.



Simplified system synthesis sequence

FIGURE A

The search beam positions were determined based upon a maximum beam packing density and an overlap value of 1/4 beamwidth for adjacent beams.

Following development of the search scan program the radar performance was evaluated relative to angle measurement capability. The use of edge point angle tracking was considered but required excessive time per target thereby limiting the number of target tracks per unit time. Sequential lobing angle tracking was selected which not only reduced the track time but improved the angle measurement accuracy.

The radar design and performance was finally established in a hostile environment including rain, ground clutter, chaff and jamming. In addition the design impact of achieving low probability of intercept (LPI) and a target identification capability was evaluated.

3.5.2 SEARCH SCAN PROGRAM

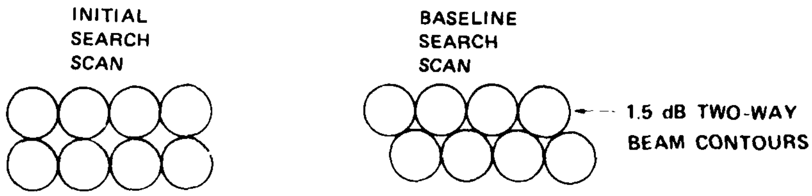
The search scan program utilizes the available energy most efficiently while fulfilling the coverage requirements.

The baseline concept utilizes electronic beam switching in both azimuth and elevation. Beam directions can be selected on a random access basis and a fixed quantity of beam directions are available. The initial search scan program which was developed positioned the beams in rows and columns. This scan configuration results in relatively large regions of reduced antenna gain and deep nulls within these regions. This was true even with beam directions spaced at one-half beam width distances. The scan program was modified to allow alternate elevation rows to be offset by one-quarter of a beamwidth. This change resulted in a more uniform detection sensitivity with target angle and a more effective search scan.

A comparison of the "initial" and "baseline" scan techniques is illustrated in Figure A. The elevation beam step size is reduced due to the more efficient beam packing. This of course increases the number of required elevation steps to achieve the required elevation coverage. For the baseline aperture, 13.3-feet by 12-feet, the number of elevation beams has increased from 19 to 22 and the search time is approximately 8 seconds.

Referring again to Figure A, the initial scan technique used an available elevation beam step resolution of 0.125 beamwidth. This step size was for edge point tracking which was discarded in favor of sequential amplitude lobing for the baseline scan technique. The available azimuth beam step resolution was increased (to 1/4 beamwidth) in the baseline approach to provide additional angle accuracy in the fine angle track mode. The baseline scan technique not only provides better (more uniform) search coverage but results in increased angle accuracy.

A pictorial representation of the scan program is illustrated in Figure B. The program shown is for the 11 ft by 7 ft array. A similar pattern would be obtained for the baseline 12 ft by 13.3 ft array.



	INITIAL	BASELINE
ELEVATION STEP	.5 BW	.433 BW
NUMBER OF ELEVATION BEAMS IN 20°	19	22
SEARCH TIME	6.675 SECS	7.97 SECS
WIDEST ELEVATION BEAM WIDTH	13.1°	13.1°
ELEVATION STEP RESOLUTION	.125 BW	.433 BW
AZIMUTH STEP RESOLUTION	.5 BW	.25 BW

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Figure A. Comparison of initial and baseline scan program

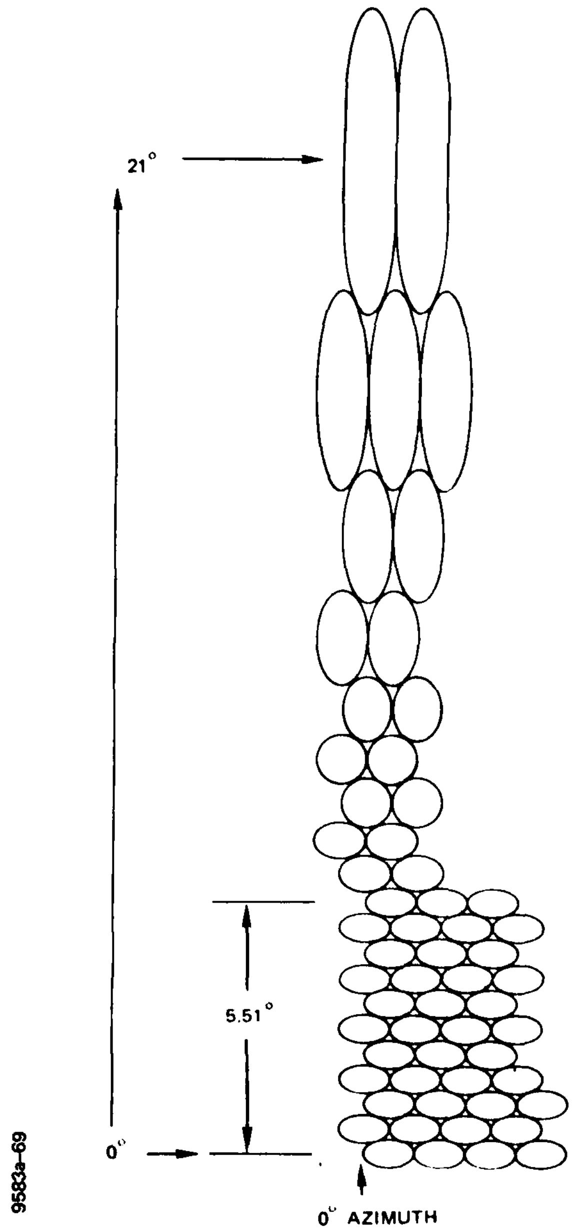

Figure B. Elevation scan pictorial for 1.5 dB two-way beam contours and 11 ft by 7 ft aperture

3.5.3 COARSE (SEARCH) ANGLE MEASUREMENT SCAN PROGRAM

The search scan program maximizes the angular accurach obtained.

The baseline system design employs sequential amplitude comparison to obtain target angle information in both the coarse (search) and fine (track) angle measurement mode.

In the search mode, target return amplitude is stored on all detected targets and this data is accumulated in the normal search sequence. For an amplitude comparison measurement, a beam separation of 0.8 beamwidth is nearly optimum when the target is not tracked at null crossover. The beam separation increments available in azimuth and elevation are respectively 0.5 and 0.433 beamwidths in the search mode.

The beam separations used in the computation of angle accuracy in the search mode are: 1 beamwidth for azimuth and 0.866 beamwidth for elevation, respectively. Actually, all beams in the vicinity of the target could and should be used in computing the target angle. Figure A is a cross section of the antenna beam search scan program in azimuth. The beam step sizes are 0.5 beamwidth resulting in an alternate beam cross over (two way) of 6 dB. In the figure a target is shown in a typical direction resulting in signals S0, S1 and S2 for each of the indicated beam positions. Beam positions "1" and "2" and signals S1 and S2 would in this case be used for the angle measurement. Actually, S0 could also be used along with signals obtained in adjacent scans above or beneath the plane of the paper. The angle accuracy curves, presented earlier in this report, were computed based upon using only beams separated by 1 beamwidth in azimuth (i.e., beams "1" and "2" for the target direction indicated. As the target moves in angle beams "1" and "2" would remain optimum over some determinable target angle area. Outside of this area other beam sets would become optimum. Figure B illustrates the target areas for which search azimuth angle measurements would be made by beams "1" and "2".

Targets within the indicated area will be measured with minimum error by beams "1" and "2". Targets outside of this area would be measured by other beam pairs. A corresponding search elevation area is presented in figure C for beams "3" and "4".

The search angle accuracy was computed by averaging the angle errors over the areas indicated. In general, targets located near the center of these areas will be measured to greater angular accuracy than targets near the edge.

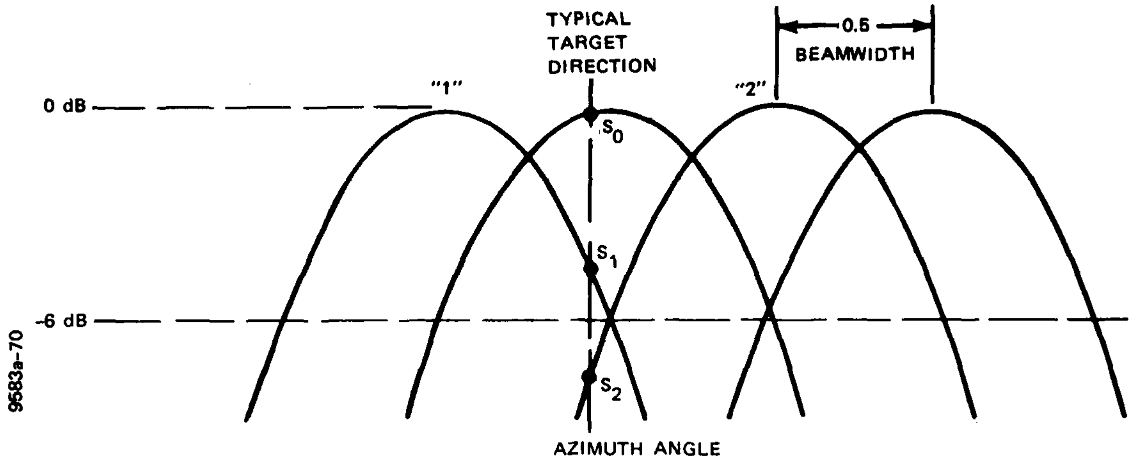

Figure A. Angle measurement technique

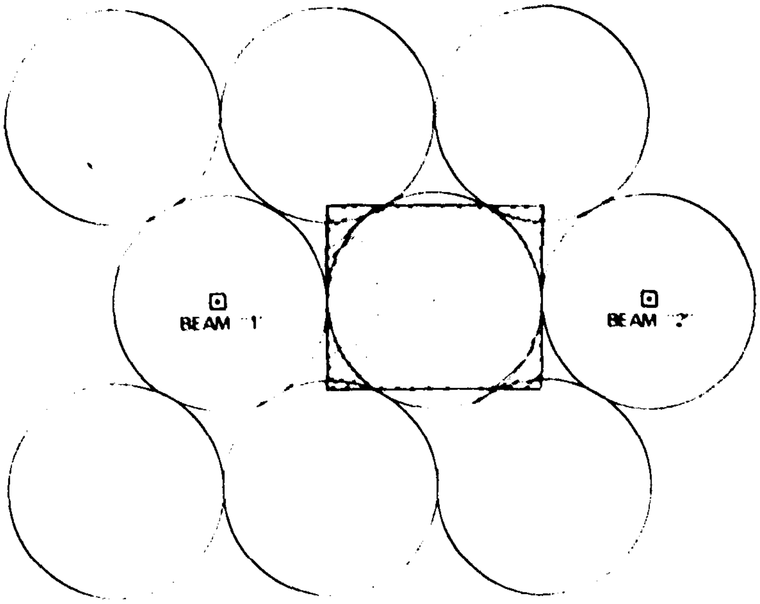

Figure B. Search azimuth angle target area for beams "1" and "2"

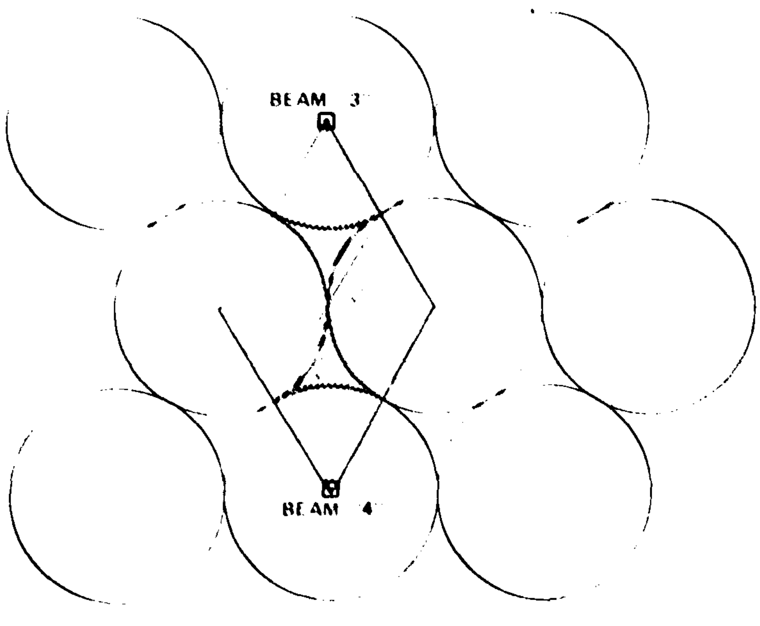

Figure C. Search elevation angle target area for beams "3" and "4"

3.5.4 FINE (TRACK) ANGLE MEASUREMENT SCAN PROGRAM

A special scan program, used only on selected targets, yields the highest angular accuracy.

If greater angular accuracy than can be obtained in the search mode is desired, then one can utilize a fine angle measurement.

In the fine angle measurement mode the available azimuth beam step increment is reduced to a value of 0.25 beamwidth. This technique permits a more optimum beam alignment for both azimuth and elevation angle measurements and reduces the target location areas per beam pair. Furthermore, the more optimum beam separation of 0.75 beamwidth can now be used for the azimuth angle measurement (compared to 1 beamwidth).

The fine angle measurement areas for azimuth and elevation are illustrated in Figures A and B. Again the angle accuracies were computed and averaged over these areas for the respective beam positions shown. Azimuth beam positions can occur as shown or be stepped one-half the distance between centers illustrated. Thus, the beam "1" center in Figure A is an adjacent beam position that can be obtained in fine track.

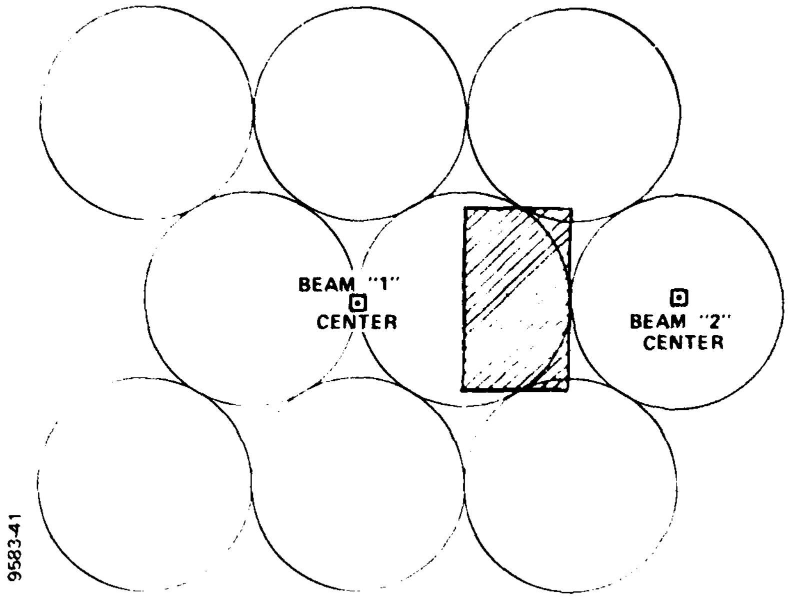

Figure A. Fine-track azimuth target area for beams "1" and "2"

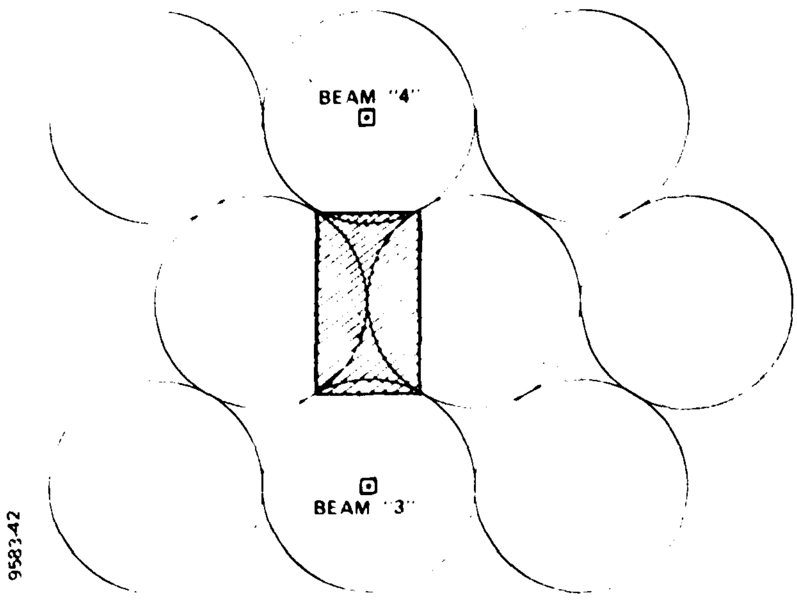

Figure B. Search elevation angle target area for beams "3" and "4"

Section 4

WAVEFORM DESIGN CONSIDERATIONS

4. WAVEFORM DESIGN CONSIDERATIONS

The technology requirements for advanced waveform techniques were determined through an assessment of the baseline system performance.

The choice of a suitable waveform is one of the more important aspects of radar design because the waveform not only establishes an upper performance bound on target parameter extraction and background rejection, but it also bears heavily upon system cost. The problem is compounded by the desire for multifunction radar operation (preferably in a single frequency band), and by the steadily increasing nature of the threat. This situation imposes the need for balanced management of radar resources to optimize target detection and track within a dynamic clutter/ECM environment. In this context, the transmitted waveform represents just one facet of the available radar resources.

The waveform design task was concerned primarily with identifying advanced technology concepts required to meet expected post-1985 requirements for the following key environments:

a) Standard; consisting of in-the-clear and ground clutter

b) Rain

c) Chaff

d) Barrage jamming: both escort and stand-off

e) Low probability of intercept (quiet emission)

f) Non-cooperative target recognition.

The boundaries of the above environments are depicted in the accompanying range height chart and plan view diagram (Figures A and B). The range-height profile is shown out to 200 nmi in range and 100,000 feet in height. Ground clutter is limited to a range extent of 50 nmi, and to an elevation not exceeding 3.5 degrees. The upper limit of elevation would be imposed by nearby high mountainous terrain. Rain clutter is restricted to heights below 20,000 feet, and to an extent of no more than 50 nmi in the plan view. The diagrams also note the possibility of bimodal rain and ground clutter at close range.

A chaff cloud containing barrage jammer aircraft is indicated at a range of 150 nmi and lying between 30,000 and 40,000 feet altitude. The range extent of the chaff corridor is typically 30 nmi, and extends between 25 to 40 degrees in the azimuth plan view.

The primary assessment of the baseline system operation was confined to the following:

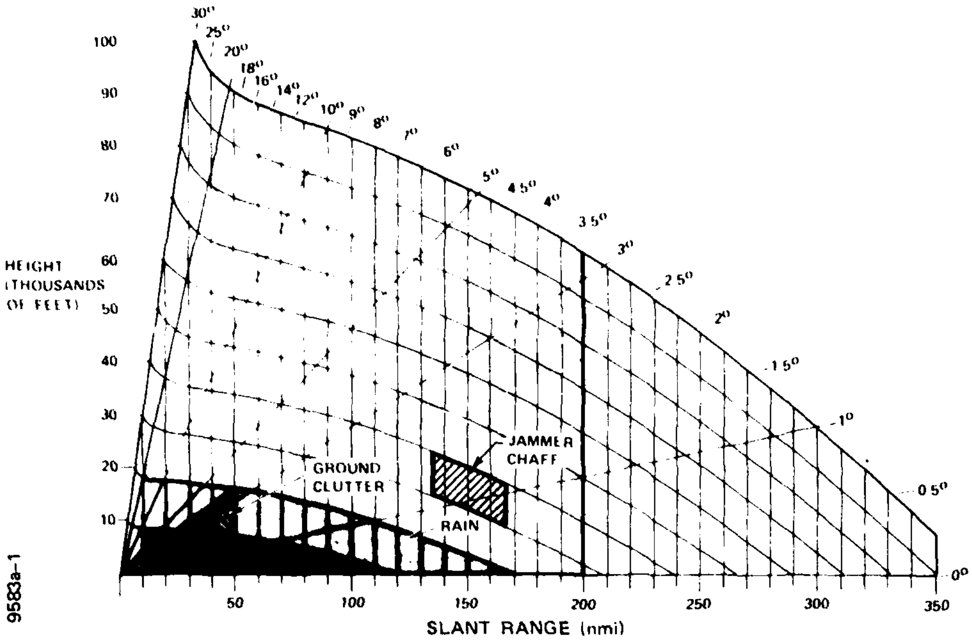

Figure A. System environment range height chart

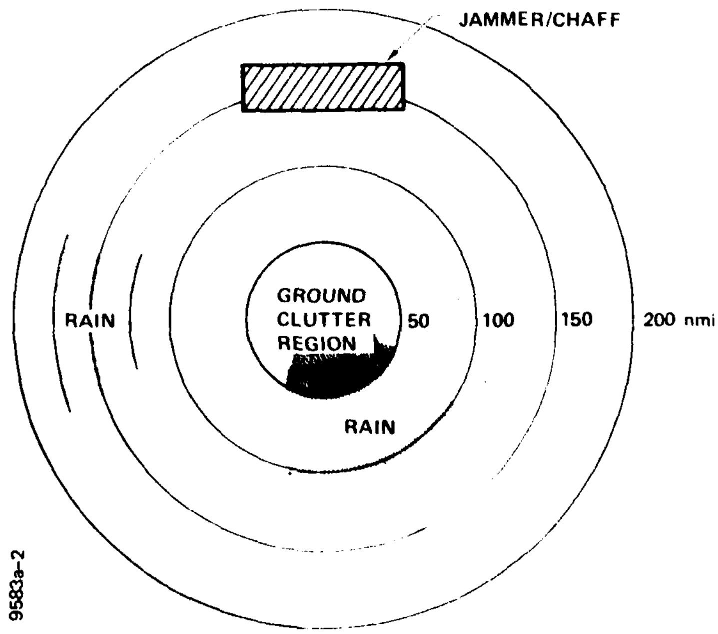

Figure B. System environment plan view diagram

a) Search requirement

b) Limitation of the clutter processing bandwidth to no more than 13 MHz. This was based upon the desire to bound processor cost by avoiding problems associated with distributed target processing; high speed target range bin velocity straddle with accompanying angle extraction association, and tempered by the expectation that near gigabit type logic will not be available in the 1985 time frame.

c) Utilization of much wider bandwidth signals. This was investigated and assessed from a technology standpoint in dealing with low probability of intercept and target recognition.

d) Detection of targets in clutter ECM was considered primarily at long range (about 150 nmi), since the effect of technological advance would be relegated to this region for the search requirement.

The waveform design investigation was then structured as follows:

a) Assess baseline operation in the various environments.

b) Where deficient, investigate techniques to meet requirements.

c) Determine, as necessary, advanced technology to implement required techniques.

The results of this investigation are reported upon in the sections following, and recommend various intrapulse and interpulse waveform designs which adapt to the changing environment. This is carried a step further in section 6.4, which presents processor configuration for implementing the suggested waveform techniques.

4.1 STANDARD ENVIRONMENT

The baseline system is capable of meeting the standard environment search requirements with available technology.

Assessments of the baseline system operation were made utilizing standard search radar equations as found in Barton[1]. These basic equations provide estimates of radar performance as limited by receiver noise, jamming, and clutter, which enables pinpointing those areas requiring substantial improvement. The standard environment search equations are listed in Tables I and II, for receiver noise and ground clutter. Table III summarizes those baseline system parameters pertinent to the search radar equations.

The equations listed in Tables I and II, as well as those utilized in subsequent sections, are written in forms which emphasize the most basic requirements placed on the radar design for tracking or search in different environments. By segregating the various practical inefficiencies in equipment performance into loss terms, the ideal limits imposed on all types of systems can be determined.

The results do not lead to any uniquely correct solution to the common radar problems, but they have been proven useful in identifying system approaches which are at least theoretically feasible. Conversely, they may be used to identify those problems which cannot be solved by conventional or available techniques, so that the problems may be redefined to aid solution. The overall scale of the radar system can, therefore, be readily determined without recourse to detailed system design.

The basic requirement for detection of targets in the clear is given by the receiver noise limiting search equation in Table I, which sizes the required average power aperture product of the radar. Utilizing the parameters listed in Table III, this product computes to:

$$P_{AV}\, A_R = 38{,}200$$

Given a limit due to physical constraints of 8 m^2 for the effective receiving aperture, the required average power must then be approximately 4.8 kW for each of the four antenna faces which comprise the baseline design. This figure is consistent with the 5 kW per face chosen for the system.

The pertinent factor relative to clutter is the BI product (processing bandwidth times the realizable signal Processing (MTI) improvement factor). This product provides an index of processing difficulty for the receiving system, and is closely related to cost and complexity. For the parameters defined in Tables II and III, the BI product is:

$$BI = 10^{10} = 100 \text{ dB Hz}$$

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[1]Barton, D.K. [1974], "Radars Volume 2, The Radar Equation", Chapter 10, Artech House, Inc., 1974

Table I. Receiver Noise Search Requirement

$$P_{AV}\,A_R = \frac{4\pi\psi_s\,kT_I\,R_M^4\,DL_s}{\sigma t_s}$$

A_R = effective receiving aperture

P_{AV} = average transmitter power

k = Boltzmann's constant

D = energy ratio required

L_s = total search loss

T_I = effective input noise temperature

R_M = maximum range of radar

t_s = total search time (frame time)

σ = target cross section

ψ_s = solid angle searched

Table II. Ground Clutter Search Requirement

$$BI = \frac{A_M\,R_M\,R_U\,\sigma^o\,DL_{IC}}{\sigma t_s}$$

B = signal processing bandwidth

I = Steinberg's MTI improvement factor

AM = azimuth search sector

D = energy ratio required

L_{IC} = integration loss in clutter

R_M = maximum range of radar

R_U = unambiguous range

t_s = total search time (frame time)

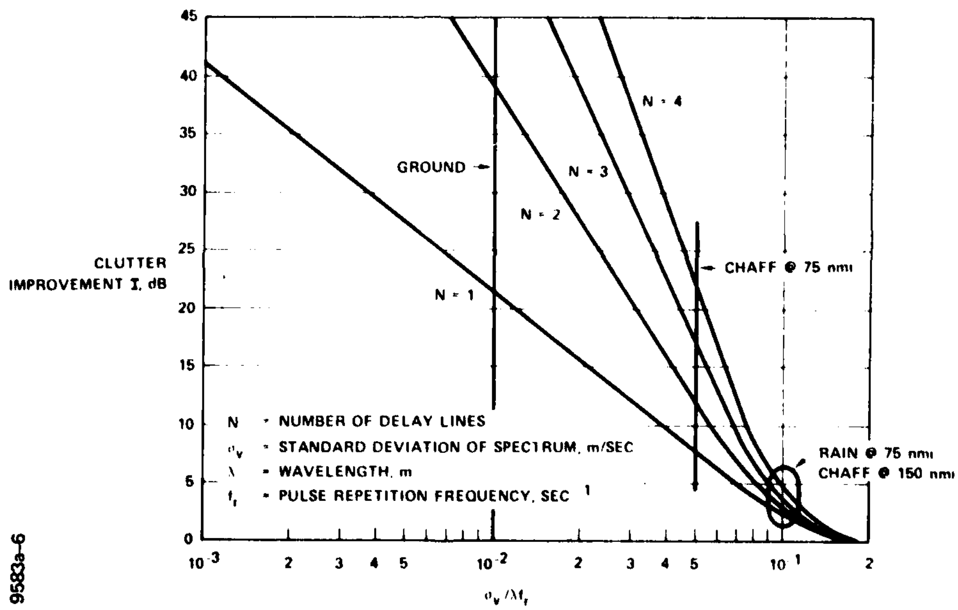
σ = target cross section

σ^o = surface clutter reflectivity

Table III. Radar Search Baseline Parameters

Parameter	Value
Frequency	5500 MHz
Search Time	t_s = 7 secs
Coverage	0 to 20° Elevation 360° Azimuth R_U = 200 nmi
Target	Swerling 1, σ = 3 m^2
Detection	P_D = .5, P_{FA} = 10^{-6} @ R_M = 175 nmi
Receiver Aperture	$A_R \leqslant 8\ m^2$/FACE
Noise Figure	F = 3 dB
Losses	$L_s \leqslant 19$ dB
RF Plumbing	8 dB
Beam Shape	1.5 dB
Processing	6 dB
Troposphere	3.5 dB

The ground clutter model is typical for a C-band ground based surveillance radar, having a Weibull distribution with an 85th percentile σ^o of -22 dB. With a Gaussian spectrum spread of 10 Hz, an improvement factor of at least 35 dB can be realized with a conventional 3-pulse canceller. This is shown in the figure below (extracted from Nathanson [1969]), noting that the $\sigma_v/\lambda f_r$ ratio for ground clutter is nominally 10^{-2} for a prf of 400 Hz. With this value of I, the processing bandwidth need be only 3 MHz. The 95th percentile of the clutter distribution, σ^o of -17 dB, can likewise be handled with a processing bandwidth of 10 MHz. It should be noted that the overall system processing bandwidth for the standard environment is equivalent to four times the signal bandwidth (B), since each antenna face requires its own processor.



Delay line canceller improvement factor

4.2 RAIN ENVIRONMENT

Long range detection in rain can be accomplished by a combination of adaptive polarization processing and spectral filtering.

The radar search equation in Table I shows the pertinent parameters for volume clutter, with the reflectivity coefficient shown for a 4 mm/hr rainfall. The standard equation as found in Barton[1], is modified by a noise limit factor (NLF), to take into account the effect of receiver noise associated with long range target detection. At 150 nmi, the NLF is approximately 3.4 dB. This results in a BI product of 92.4 dB Hz.

Using a standard shear model for rain at 150 nmi (Nathanson[2]), there results a clutter spectrum which is nominally uniform over the 400 Hz prf region. Referring back to Figure A in Section 4.1, there will then be essentially zero dB improvement utilizing conventional MTI cancellers. With the use of circular polarization (CP) for the transmit waveform, the rain backscatter can be reduced by about 15 dB. This improvement results in a processing bandwidth requirement of 55 MHz, which is considered too high for a reasonable cost processor application (this constraint was imposed in Section 4).

Since the rain clutter spectrum is essentially like 'white' Gaussian noise over the 400 Hz prf band, a coherent 8-point FFT filter will yield an improvement of 9 dB. This factor results in B equal to 7 MHz, which is comfortably within the 13 MHz bandwidth constraint. Utilization of an 8-pulse waveform with CP is then one solution for long range detection in the 4 mm/hr rain environment. The necessity for CP will affect antenna design and leads ultimately to the concept of an adaptive polarization waveform. Adaptive polarization arises from the need for CP in rain, and for more linearly polarized waves for target detection in the clear and most notably in chaff (see Section 4.3).

The baseline system operation in rain was also assessed at a range of 75 nmi, for which the BI product becomes 82 dB Hz. It is of interest to note that the use of CP is sufficient to result in a 5 MHz processing bandwidth. Although spectral filtering is not required, there will be a typical 5 dB loss relative to receiver noise which can be recovered (if desired) by utilization of an 8-pulse canceller filter. Use of this filter would also enhance rain clutter rejection by an additional 5 dB.

Within a detection range of 50 nmi, a bimodal situation exists between rain and ground clutter. This condition can be readily met by employing an 8-pulse, near optimum filter design. Use of CP would further enhance the filter improvement factor. The issue of bimodal filter coupled with polarization processing will be discussed in Section 4.3 for the chaff environment. Various waveform approaches for target detection in rain are summarized in Table II.

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[1] Ibid. section 4.1.

[2] Nathanson, F. E. [1969], 'Radar Design Principles', Chapter 9, McGraw-Hill, Inc., 1969.

Table I. Volume Clutter Search Requirement

$$BI = \frac{\psi_s R_M^2 R_u \eta D L_{IC}}{\sigma t_s} \cdot (NLF)$$

B = signal processing bandwidth

I = Steinberg's MTI improvement factor

D = energy ratio required

L_{IC} = integration loss in clutter

R_M = maximum range of radar

R_u = unambiguous range

t_s = total search time (frame time)

η = volume clutter reflectivity

ψ_s = solid angle searched

σ = target cross section

NLF = noise limit factor

Table II. Rain Backscatter Approach

Range	BI	Filter	Polarization	B
150 nmi	92.4 dBHz	MTI Canceller I = 0 dB	CP Gain = 15 dB	55 MHz
		8-point FFT I = 9 dB	CP Gain = 15 dB	7 MHz
		8-point FFT I = 9 dB	Optimum Dual Channel Gain = 20 dB	2 MHz
		4-point FFT I = 6 dB	Optimum Dual Channel Gain = 20 dB	4.3 MHz
75 nmi	82 dBHz	None	CP Gain = 15 dB	5 MHz
		8-point Canceller I = 5 dB	CP Gain = 15 dB	1.6 MHz
		None	Optimum Dual Channel Gain = 20 dB	1.6 MHz

Although these approaches differ, it would appear that an 8-pulse waveform with CP or adaptive polarization should be applied in all mapped regions of rain. This approach would avoid overcomplicating the waveform decision process. Since the prf can remain range unambiguous, the filter weights can be readily adapted as a function of range to the bimodal case, and to estimates of the rain spectrum at medium and long ranges.

There is a penalty associated with the 8-pulse mode in that additional time must be spent in regions of rain. For example, each 15 degree azimuth zone would require an additional 0.5 seconds of search time. If it were also desired to operate at the baseline pulse compression switching rate of 13 MHz, then a target travelling at 1000 m/sec could traverse two range bins during the 8-pulse sample. This would complicate the processing and impose an additional velocity straddle loss. It was noted, however, that the required value of B need be only 7 MHz, such that a lower code switching rate could be used with the rain waveform.

Further study would be required to determine the efficacy of an adaptive dual channel polarization mode. If an additional 5-10 dB can be realized in reducing rain backscatter relative to CP, then it would be possible to reduce processor complexity by using much lower processing bandwidths. If additional target enhancement also accrues over CP relative to receiver noise, then the 8-pulse mode may be reduced to either 4 or 6 pulses.

4.3 CHAFF ENVIRONMENT

Long range target detection in high density chaff can be accomplished through bimodal filtering of an ambiguous prf waveform in conjunction with adaptive polarization techniques to minimize processing speed requirements.

The radar search equation for the rain volume clutter also applies to chaff. For high density chaff, the reflectivity coefficient utilized was 10^{-7}, twice that for 4 mm/hr rainfall. Consequently, the resulting BI product for chaff is 95.4 dBHz.

A spectral spread of 80 Hz (1σ) was used for the chaff cloud at 150 nmi. With a prf of 400 Hz, this allows for only 6 dB of improvement factor with an 8-point FFT canceller. The required processing bandwidth would then be nominally 1 GHz. Even with optimum dual channel polarization processing yielding an additional 10 dB of signal-to-chaff improvement, the required value of B is still high, in the order of 60 MHz.

Much greater improvement factors can be obtained with spectral filtering by doubling the prf to 800 Hz. Aside from creating a range ambiguous signal, there now exists the potential for ground clutter foldover. This condition is shown in Figure A which maps target and chaff returns at 150 nmi into the ground clutter region at 50 nmi. Note that there is a 3 dB decrease in both s/n and c/n ratios on a per pulse basis when going from a 400 Hz to an 800 Hz prf. This is a consequence of operating the solid state baseline transmitter at fixed peak and average power levels. A doubling of the prf then results in halving of the energy per pulse.

Assuming the bimodal chaff and ground clutter returns as shown in Figure A for a target at 150 nmi, the ground clutter-to-noise ratio is 50 dB, chaff-to-noise is 28.5 dB, and s/n is 13 dB (this is based on B = 10 MHz). An 80 Hz, 1-sigma spectral spread for the chaff, a 5 Hz spread for ground clutter with a dc-to-ac spectral component ratio of 3.4:1 was used for the design of an optimum 8-pulse bimodal clutter filter (OFT). Design of these filters is patterned after the method of DeLong and Hofstetter[1], and was developed by ITT Gilfillan for various system applications. Under the above conditions, the average greatest improvement factor (AGI) for the filter bank was 46 dB[2], resulting in an output

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[1]DeLong F.E. and Hofstetter, E.M. [1967], 'On the Design of Optimum Radar Waveforms for Clutter Rejection IEEE Trans. Information Theory, Vol. IT-13 No. 3, July 1967.'

[2]For a single channel clutter filter such as a canceler the improvement, due to clutter filtering at a particular signal frequency, can be defined as the ratio of the output signal-to-clutter-plus-noise ratio to the input signal-to-clutter-plus-noise ratio. The improvement factor is given by averaging the improvement over all signal frequencies. This definition of improvement factor can be extended to multiple channel clutter filters such as the OFT. As any particular signal frequency is applied to all filters, the improvement due to each filter can be separately determined. When the filter outputs are properly normalized with respect to their residues of clutter-plus-noise and combined on a greatest-of basis, the average detection statistics are determined by the filter giving the greatest improvement at that particular signal frequency. The AGI (Average Greatest Improvement) is obtained by averaging the greatest improvement over all signal frequencies. AGI is equivalent to the improvement factor of a single channel clutter filter.

s/c+n ratio of 9 dB. This is 4 dB short of the desired value of 13 dB. In actual design, the unrealizable OFT is replaced by a near optimum filter bank (NOF), which entails a further loss of nominally 2 dB. The net discrepancy of 6 dB would result in an increase of the 10 MHz assumed processing bandwidth to 40 MHz.

A second OFT design was synthesized based on utilizing dual channel polarization processing where it is assumed that the chaff backscatter is decreased by 10 dB. Results of the computer simulation are shown in Figure B. The AGI has been improved to 50 dB. A design using the NOF filter bank would now require a processing bandwidth of 15 MHz, which is quite close to the desired upper limit of 13 MHz.

A final OFT design was made using a 1600 Hz prf without polarization processing. The target was placed at 130 nmi to accentuate additional ground clutter backscatter. The relevant signal and clutter levels are shown in Figure A. The OFT computer plots are shown in Figure C, where the AGI is now 56 dB. With the given input parameters, the output s/c+n ratio is 15 dB. Given a 2 dB loss for the NOF, the desired 13 dB ratio will be met with a 10 MHz processing bandwidth. This bandwidth can be reduced further through the use of polarization processing to minimize chaff backscatter.

Long range target detection through high density chaff is, therefore, possible with moderate processing bandwidths at an ambiguous prf of 1600 Hz. Polarization processing will enhance target detection in the chaff and or permit operation at reduced processing bandwidths. Further study is necessary to trade the dual channel configuration cost against

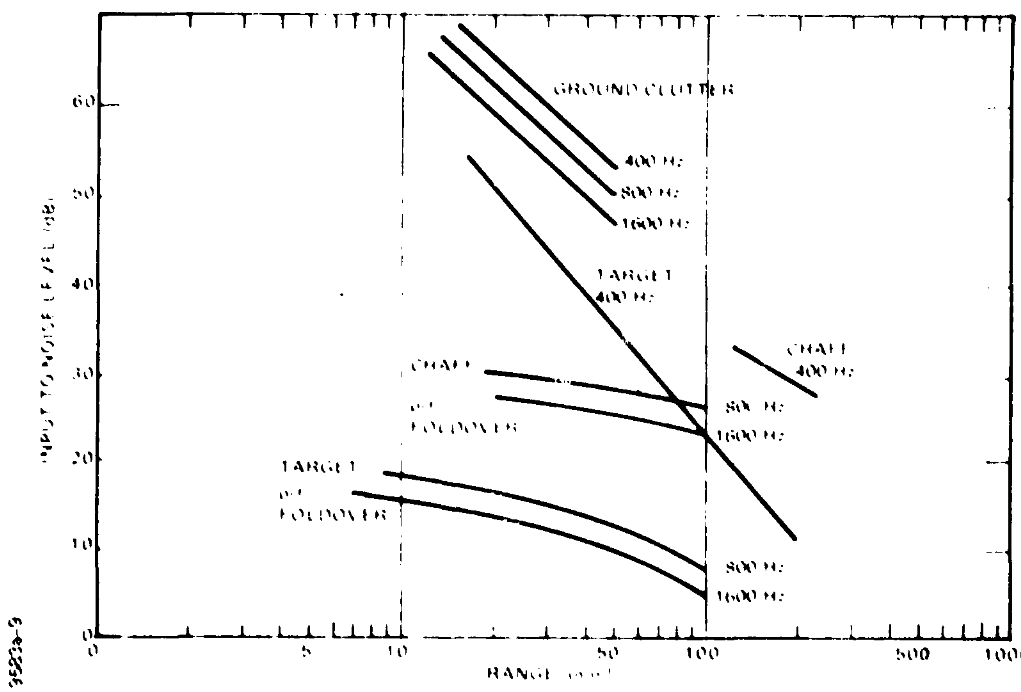

Figure 4 Ambiguous prf target/chaff foldover levels (B = 10 MHz)

processor cost. Detection through low density chaff would be handled in the same way, noting that very little improvement can be achieved with spectral filtering at the 400 Hz prf. At short ranges, the chaff spectral spread diminishes such that greater than 15 dB of improvement can be obtained with conventional 8-point canceller filters. Since the required BI product is now reduced to 85 dBHz, this permits utilization of a 10 MHz processing bandwidth with a range unambiguous prf. The various filter polarization approaches are summarized in Table I.

The technological implications relative to implementing the parallel bank of near-optimum-filters is discussed in Section 6.4. The major issues relate to wide dynamic range (53 dB ground clutter-to-noise ratio), high processing speed (upper limit of 13 MHz), and costs of pulse compression networks for coded intra-pulse waveforms.

The resolution of the range ambiguous 1600 Hz prf involves an added degree of processor complexity, but not any significant technological problems. It is noted that the 8-pulse sequence will involve a stagger ratio to improve the target velocity response. This prf stagger can then also be used to resolve ambiguous range using well known standard techniques. The transmission of 16 pulses per angle cell will necessitate a slowing of the search within the chaff cloud noting, however, that the prf has been increased by a factor of four. Since the baseline system scan is programmed for an average of 2 pulses per bean position, the search time need only double within the chaff cloud, adding less than 0.5 seconds per typical chaff corridor to the search time.

Table II summarizes the technology assessment relative to chaff processing. Various approaches are listed which offer alternate methods for long range target detection. These would be of interest for future study in cost trade analyses relative to the suggested bimodal filter high prf implementation.

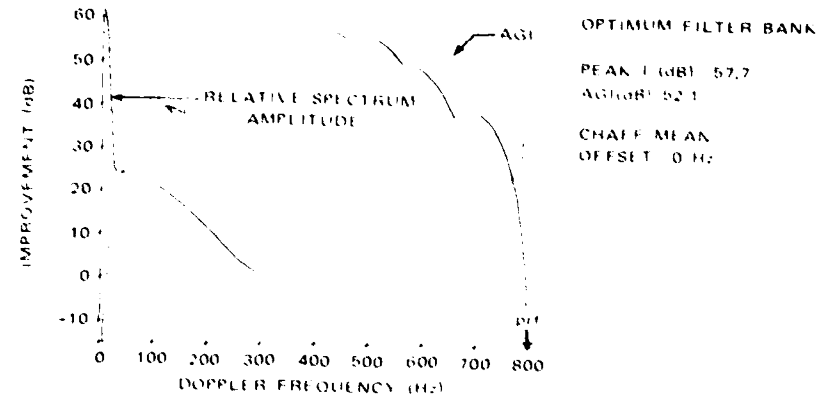

Figure B-1

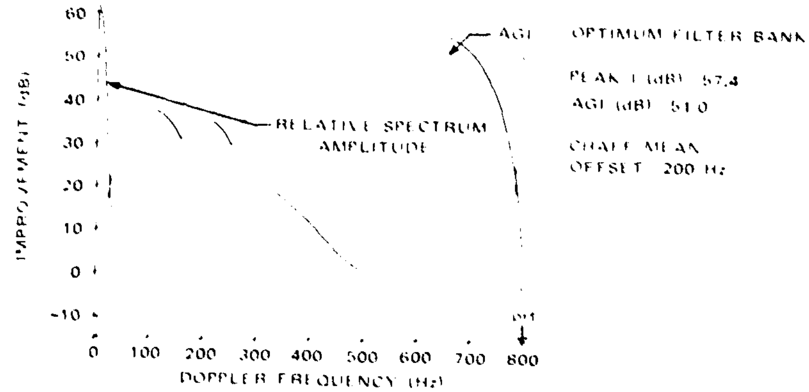

Figure B-2

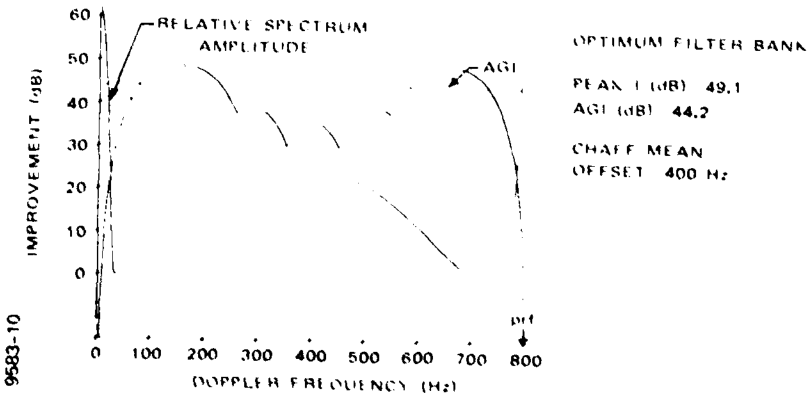

Figure B-3

Figure B. ***Bimodal filter at 800 Hz prf with polarization processing***

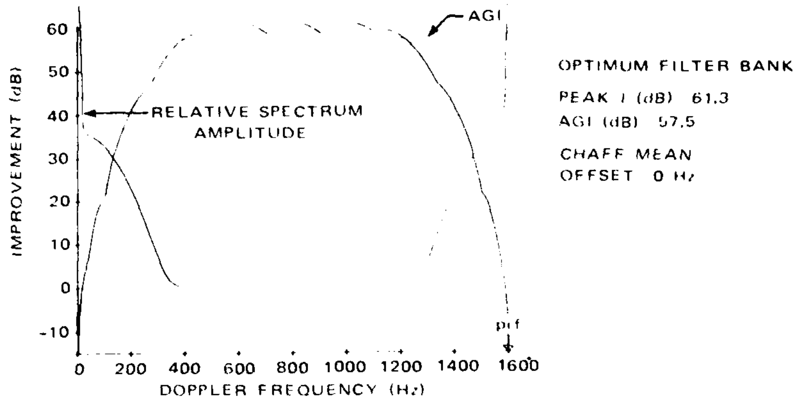

Figure C-1.

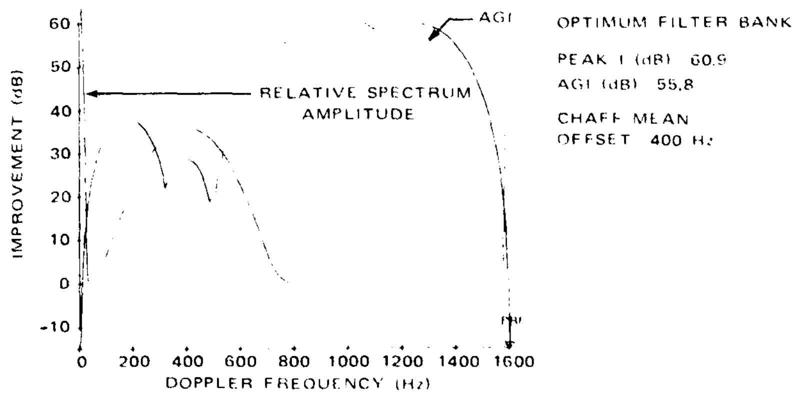

Figure C-2

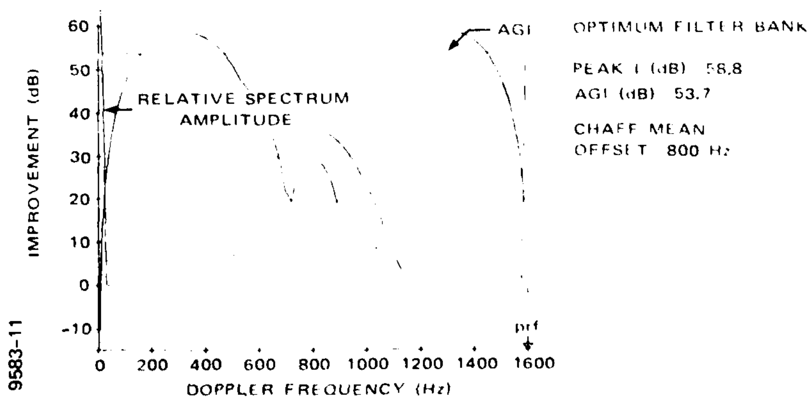

Figure C-3

Figure C. Bimodal filter at 1600 Hz prf

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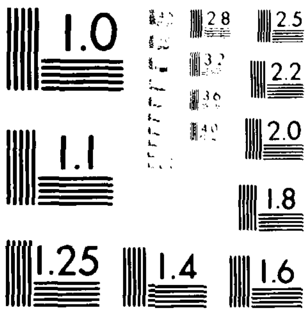
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

Table I. Chaff Backscatter Approach

Range	BI	Filter	Polarization	prf	B
150 nmi	95.4 dBHz High Density	8-Point Canceller 1 = 6 dB	Optimum Dual Channel 5 dB ⩽ 1 ⩽ 15 dB	400 Hz	60 MHz
		8-Point Bimodal AGI = 44 dB	Linear	800 Hz	40 MHz
		8-Point Bimodal AGI = 48 dB	Dual Channel 1 = 10 dB Signal-to-Chaff	800 Hz	15 MHz
		8-Point Bimodal AGI = 54 dB	Linear	1600 Hz	10 MHz
75 nmi	85 dBHz High Density	8-Point Canceller 1 ⩾ 15 dB	Linear	400 Hz	B ⩽ 10 MHz
150 nmi	83 dBHz Low Density	8-Point Canceller 1 = 6 dB	Dual Channel 5 dB ⩽ 1 ⩽ 15 dB	400 Hz	5 MHz
		8-Point Bimodal AGI = 54 dB	Linear	1600 Hz	0.5 MHz

NOTE: Bimodal Filter for Ground Clutter & Chaff
AGI = Average Greatest Improvement Factor

Table II. Chaff Technology Assessment

▪**Problem**

- **Unambiguous long range detection not feasible with conventional Doppler processing**

Approach	Need	Remarks
Adaptive dual channel polarization processing	Real time measure of chaff scattering properties and algorithm development	Realizable 5-10 dB improvement may not be sufficient
8-Point Canceller filter and wideband processing (>50 MHz)	Components for 20 dB dynamic range high speed processor and high TB pulse compression	Distributed target and velocity loss considerations
Within the pulse Doppler processing	High speed filter bank processing	Trade range cell size vs Doppler filter gain vs velocity effects
Ambiguous range processing	Method minimizing ground clutter	Ground clutter foldover
• Spatial rejection	Adaptively move antenna sidelobes to minimum in mapped regions of heavy ground clutter.	Efficacy depends upon terrain masking relative to chaff corridor
• Code diversity	Separate ground and chaff returns by code and range	Need dual receivers, good code selectivity
• Bi-modal Doppler processing	Components for wide dynamic range processor, 60 dB stability	Conventional implementation

4.4 BARRAGE JAMMING

Barrage jamming can be countered by resource management involving frequency/ polarization agility, search speed variability, and antenna sidelobe placement, aided by mapping of the jammer influence sensitivity region.

The search equations for barrage jamming, both self-screen and stand-off are listed in Table I. It should be noted that these equations assume a received jammer power density much greater than that for receiver noise. A modifying factor should be applied when jammer and receiver noise levels are nominally equivalent, and would apply particularly to stand-off sidelobe jamming.

Assuming an effective radiated jammer power density of 100 watts/MHz (typical state-of-art aircraft jammer), the self-screen burn through at 150 nmi would require a P_{AV} of 30 MW. This underscores the basic futility of developing any reasonable SSJ scheme for extracting range information with a single radar sensor. The same radar main beam situation applies to the jammer zone depicted in Figures A and B of Section 4, which typically contains 30 escort jammers distributed within a region 100 nmi wide by 30 nmi deep. Azimuth and elevation jam strobe extraction techniques may prove effective for triangulating on the SSJ, depending upon whether adequate angle resolution is available within the densely packed jammer zone. Efficient angle extraction algorithms have been developed by ITT Gilfillan on other programs, and could be utilized with minor modification for advanced radar netting application.

A primary ECM threat would be to mask targets of interest by stand-off-jammers (SOJ) operating at distances relatively removed from weapon intercept ranges. Assuming that jamming occurs within the intercardinal region of the receiving antenna where the rms sidelobes are down 50 dB, then negligible performance degradation will occur when a single SOJ is operating at a range of 150 nmi with a power density of 100 W/MHz. The figure-of-merit which is of interest, however, is the jammer power density necessary to degrade radar detection range by 50 percent. At a standoff range of 150 nmi, this number is 19kW/MHz. It is not expected that a single aircraft jammer will have that capability in the post-1985 time frame. However, a multiplicity of SOJ's could seriously erode radar performance. The allowable degree of system degradation would require a detailed analysis of the interaction between the operational and threat scenarios. There are, however, various techniques which can be implemented to further nullify the effects of jamming. Most of these are not directly related to waveform design but are summarized below and in Table II.

The baseline system already has the capability for operating over a wide frequency band, which provides the positive effect of diluting available jammer power density. Polarization agility would likewise increase the cost to the jammer threat. The potential also exists for target cross section enhancement through polarization processing, such that the available radar power can be utilized more effectively. The level of such improvement remains to be determined through ongoing ITT Gilfillan study efforts in this area.

Table I. Barrage Jamming Search Requirement

$$P_{AV}B_J = \frac{P_J G_J \psi_S R_M^2 \, DL_4}{\sigma t_S} \qquad \text{(Self-Screen)}$$

$$P_{AV}G_S B_J = \frac{P_J G_J \psi_S R_M^4 \, DL_4}{R_J^2 \, \sigma t_S} \qquad \text{(Stand-off)}$$

P_{AV} = average transmitter power

G_s = mainlobe/sidelobe gain ratio

B_J = width of jammer spectrum, assumed equal to agility bandwidth of radar

D = energy ratio required

G_J = jammer antenna gain

L_4 = portion of L_S applicable to jamming case

R_J = range to jammer

R_M = maximum range of radar

P_J = total jammer power

t_S = total search time (frame time)

σ = target cross section

ψ_S = solid angle searched

Table II. Barrage Jamming Technology Requirements

Approach	Baseline	Desired	Technology
Selfscreen			
Standoff			
Higher P_{AV}	5 kW	15 kW	Cannot make range measurement Develop azimuth/elevation jam strobe triangulation network Reduce plumbing loss Hi-Power antenna components Efficient transmitter devices
Reduce Antenna Sidelobes	-50 dB	-60 dB	Maintain component tolerance over physical environment
Frequency and/or Polarization Enhancement	0	5 dB	Dual channel processing
Sidelobe Cancelling	0	5-10 dB	Multiple loop configuration Adaptive antenna nulling
Slow Search Rate	–	–	Trade time for power
Auxiliary	–	–	Monitor environment to adapt P_{AV} to jammer influence

One method of improving the ECCM radar operation lies in further reduction of the antenna sidelobes. A 60 dB sidelobe level is theoretically realizable, but would be limited by the constraints of maintaining component tolerances over the physical environment. For example, multipath in a battlefield environment limits the effective sidelobe level.

Sidelobe cancellers are a major counter to sidelobe jamming. These techniques have been generally ineffective in a multiple jammer environment and may be even more difficult to implement in a mobile situation in which the radar site geometry is continually changing. It may be more effective to shift the sidelobe structure of the antenna to minimize jammer input. This technique would be aided by a mapping of the jamming influence upon radar sensitivity. This mapping procedure has been developed by ITT Gilfillan for inclusion in its series 320 radar. The problems associated with adaptive sidelobe nulling, especially in a multiple jammer environment, have not yet been sufficiently resolved to determine its effectivity.

Lastly, there can be an operational trade-off between detection sensitivity and search speed. Here again, the jamming influence mapping can be used to adapt the search rate in some proportion to the level of jamming. More energy on target can be expended in heavy jamming zones at the expense of a lower search data. rate.

4.5 LOW PROBABILITY OF INTERCEPT

The low probability of intercept requirement can be partially satisfied by utilizing noiselike waveforms over wide instantaneous bandwidths, and possessing time-bandwidth products of 45 dB or greater.

The low probability of intercept (LPI) or "quiet transmission" requirement imposes rigorous demands upon waveform design and processor configuration. In essence, it is desired to detect targets at long range while maintaining a transmit waveform signature which cannot easily be extracted by hostile anti-radiation devices such as the ARM. A study on the subject of Quiet Radar was performed by ITT Gilfillan for the Army Missile Command, and is denoted as reference MICOM . Various of these study results are applied to the discussion below.

Table I contains a fundamental LPI signal relationship between the radar parmeters* and those of the threat intercept ESM receiver. The key trade-off items are the desired quiet range, the ESM receiver sensitivity, and the $G_R G_P$ product of the radar. This parametric relationship insures sufficient target s/n at the radar for the desired probability of detection, while maintaining a sufficiently low ratio of radar power density to ESM receiver noise density to meet the LPI criterion. Since the radar receiving antenna gain is generally restricted (40 dB for the baseline system), the radar processing gain becomes the key design parameter. The value of G_P is the coherent gain that the radar processor achieves relative to the target signal, compared to the presumed non-coherent capability of the ESM receiver relative to the radar signal. If the ESM receiver can extract somewhat more energy from peculiarities in the radar waveform (higher level prf components for example), then the net achievable G_P would be commensurately less.

Using the baseline radar parameters and a state-of-art superheterodyne ESM receiver (-75 dBm sensitivity over a 100 MHz bandwidth), the $G_R G_P$ product is 117 dB for target detection at 175 nmi. With a 40 dB antenna gain, the required processing gain becomes 77 dB. This gain is not considered achievable within the foreseeable future, such that LPI within the radar mainbeam would not be possible.

There are advantages if quiet operation can be maintained in the radar transmitted sidelobes. With an rms level of 50dB, the required Gp for LPI in the sidelobes reduces to the more practical value of 27 dB. This G_P, however, still relates to both target and ESM detection at 175 nmi. From a system standpoint, the desired operation would be target detection at 175 nmi, with LPI at a much closer range. This goal can be achieved with excess processing gain referenced to 175 nmi. Utilizing a G_P of 45 dB as an example, the quiet range reduces to the order of 50 nmi. This was obtained by first noting that the LPI equation is for CW operation, and must be modified for the higher spectral components associated with the pulse radar duty cycle. An 8 dB figure was used for this, leaving the additional 10 dB (27 + 8 + 10 = 45) for LPI range reduction. It should be realized that

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Table I. Low Probability Intercept Search Requirement

$$G_R \cdot G_P \geq \frac{4\pi \cdot R^2_M \cdot k\,Ti \cdot D \cdot L_i \cdot G_A}{\sigma_T \cdot \eta_A \cdot L_A}$$

Where:

G_R = Radar Receiver Antenna Gain

G_P = Radar Processing Gain

η_A = $\frac{-75\ \text{dBm}}{100\ \text{MHz}}$ ESM Receiver Sensitivity

G_A = 3 dB, ESM Antenna Gain

L_A = 10 dB, ESM Receiver Loss

L_i = 8 dB, Radar Loss

R_M = 175 nmi

$G_R \cdot G_P \geq$ 117 dB

$G_p \geq$ 77 dB Mainbeam LPI

$G_P \geq$ 27 dB Sidelobe LPI

With 50 dB Sidelobe, $G_P \sim 45$ dB

R_Q = 50 nmi

the 50 nmi is an estimate that can be modified in either direction depending upon the exact spectral content of the radar waveform and the capabilities of the ESM receiver.

As shown i MICOM, the processor complexity is a function of the processing gain in much the same way as it is of the BI product for the clutter environment. The 45 dB figure requires a bandwidth of 200 MHz for the DCR. This bandwidth is well in excess of that needed for range resolution or clutter processing, and presents other problems associated with range bin collapsing, velocity straddle, the necessity for parallel channel implementation, etc. Of equal importance are the problems associated with generating high G_P waveforms at these bandwidths such that their characteristics do not degrade other aspects of system performance. This problem is exemplified by the well known technique of phase code combining for the DCR waveform, which results in generally unacceptable sidelobe levels for multiple target and clutter processing.

The LPI requirement essentially calls for a noiselike waveform which exhibits a thumbtack ambiguity function. This waveform may now be practical since the time-bandwidth product (TB) should be sufficiently high for acceptable rejection of sidelobe clutter and multiple target interference. Current radar design lies more comfortably with bi-phase and FM coded waveforms. The basic technology problem with the above, however, is the cost of generating and processing these waveforms at the high speeds demanded by the wide instantaneous bandwidth requirements, coupled with a relatively long pulse duration. Detailed trade-offs between the various waveforms and their respective processor configurations demand a much more extensive study effort.

A sobering thought amidst the above speculation is that a G_P of 45 dB may not be sufficient in the post-1985 period. It is well within the realm of possibility that an ESM receiver with a sensitivity of -90 dBm will be in the inventory. For the same performance, a Gp of 60 dB would then be required. It may, therefore, be more expedient to design the system in terms of meeting the basic chaff/SOJ ECM threat, and rely upon other tactics for dealing with the LPI/ARM problem.

Table II summarizes the LPI environment assessment.

Table II. LPI Technology Assessment

- **Problem**
  - Physical Constraints Prevent LPI in Main Beam
  - Quiet Operation in Antenna Sidelobes required TB Product
    ~ 45 dB over Wide Instantaneous Bandwidth for Present Day Threat
- **Solution**
  - Partial Relief in Randomizing Signature:
    - Frequency Diversity
    - Polarization Diversity
    - Randomize Pulse Pattern
    - Randomize Search Pattern
  - Need for Noiselike Waveform with Acceptable Sidelobe Properties when Cross-Correlated for Operation in Multiple Target and Clutter Environments
  - ESM Receiver Improvement may Outpace LPI Waveform and Processor Technology Development

4.6 TARGET RECOGNITION

Coherent processing of instantaneous wideband signals derived from orthogonally polarized waveforms shows the most promise in meeting the long term target recognition requirement. A stepped frequency configuration may provide an interim solution.

The topic of non-cooperative target recognition was the subject of a study recently completed by ITT Gilfillan for RADC, under the title of Tactical Aircraft Identification[1]. This study involved an extensive literature survey. These results are summarized below relative to microwave radar techniques that show promise for use in the post-1985 time frame.

The preferred approach requires a wideband radar to provide sufficient slant range resolution of the aircraft scatterers. Coherent Doppler processing then can provide a measure of the cross range distance between scatterers in a common range cell, as the target aspect changes relative to the radar. Processing of the data results in a two-dimensional image, which can be compared against stored images of existing aircraft. There was no indication that this instantaneous wideband technique has as yet been applied successfully for two-dimensional microwave imaging of tactical aircraft.

There have, however, been U.S. Navy flight tests in the 1965 time period using an experimental high range resolution radar [see Maynard[2]]. The signal waveform was a 0.3 μsec linear FM pulse, transmitted with an instantaneous bandwidth of 600 MHz at S-band. Rate aided range tracking was used to place a 100 foot gate over the target. Detection capability was 15 miles for a 1 m^2 target. Data was recorded on returns from ten different aircraft for both nose and tail aspects. The wideband signature returns correlated with the obvious geometric features of the aircraft. A simple criterion based upon minimum deviation from the mean was utilized as a method for aircraft identification. Somewhat better results were obtained for horizontal polarization than for vertical. Although not conclusive, the results indicated a potential for classification and identification of aircraft utilizing wideband radar signatures. Additional data reduction showed the capability of extracting aircraft engine modulation from the wideband pulse-to-pulse returns.

The above wide instantaneous bandwidth effort has been replaced by a more amenable near term hardware implementation, in that stepped frequencies are transmitted over the equivalent desired RF band. Each of the frequency steps is transmitted for a period of several milliseconds, such that 'narrowband' processing can now be employed. The totality of the narrowband stepped frequency returns is shown to be equivalent to the short pulse signature obtained by the high resolution wideband radar. The trade-off requires a much longer dwell time on-target for the stepped frequency approach, as compared to the hardware

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[1]TAI [1978], 'Tactical Aircraft Identification, Final Report, Contract No. M00027-77-A-0058, YC-1, MIPR no. FQ7619800025, Project No. 2314, 12 Dec. 1978.

[2]Maynard J.H. and Summers B.F. [1967], 'An Experimental High-Resolution Radar for Target-Signature Measurements', Supplement to IEEE Trans. Aerospace and Electronic Systems, Vol. AES-3, No. 6, Nov. 1967.

complexity associated with the generation, reception, and processing of wide instantaneous bandwidth waveforms.

One such system is based on noncoherent processing of the power returns at the individual stepped frequencies. These yield an estimate of the power spectral density from the aircraft return, which then is transformable into the autocorrelation function equivalent to that of the wideband signature response. Various problems are associated with target scintillation, engine modulation, and hardware mechanization. In the latter category, availability of frequency agile oscillators and back-scanning techniques for longer dwell on target were primary problems.

An expansion of the stepped frequency technique includes measurement of phase as well as amplitude for coherent processing. This technique for radar identification of noncooperative air and surface targets uses inverse synthetic aperture imaging techniques with waveforms suitable for a wide range of existing radars. The principle features of this approach are: (1) Target images are developed from target translation and rotation motion relative to the radar platform. (2) Frequency diversity techniques are used for compatibility with existing radar designs which do not usually include wide instantaneous bandwidth. The concept is to extract target range and cross-range dimensional information produced by echoes from individual scatterers on the target. Relative range location of the target scatterers is derived by transforming the frequency diversity echo spectrum to a target range profile. The cross-range scatterer positions are then extracted from the relative Doppler velocity of the target scatterers produced by the target's rotational motion.

Assuming that reasonably noise free radar measurements can be made, there still exists the challenge of developing target recognition algorithms capable of operating in real-time with reasonable computational cost. It has been prominently noted in the survey that the use of additional discriminants such as phase and polarization information enhances target recognition, and drastically reduces the probability of misclassification. Consequently, for desired 'real-time' processing of radar data for target identification, there will be a trade between increased hardware capability to make high resolution polarization type measurements versus algorithm complexity with its associated processing time.

Based on calculations made for the stepped frequency inverse synthetic aperture approach (Wehner[3]), the integration time on aircraft targets at a range of 100 nmi would be 45 seconds. While this may be acceptable for identification of ships, it is probably unacceptable for high speed aircraft in a tactical situation. It is estimated that the non-coherent stepped frequency approach should take considerably less time, with an educated guess being in the order of 0.5-1.0 second. This latter approach would, however, require a more complex target recognition algorithm. Although the results of field tests are not known to ITT Gilfillan at this time, it is expected that it will be a number of years before the non-coherent approach is fully evaluated as to its utility. It should take even longer to evaluate the phase coherent approach.

[3]Wehner, D.R. [1978], 'Stepped Frequency Target Imaging', June 1978.

With regard to deployment in the post-1985 time frame, therefore, the more probable approach (if any) would be the non-coherent stepped frequency waveform. Typical parameters might include a 150-300 MHz bandwidth, with a step size of 2.5-5 MHz. It should be noted that this implementation lends itself to a type of linear FM waveform, although the frequencies can be stepped in a random manner. Total energy required on target for the identification process is not precisely known. Problems can arise with peak power limited transmitter devices relative to the total dwell time on target needed to meet the energy requirement. Since the target signature is heavily aspect dependent, too long a dwell may present severe association problems with high speed maneuvering targets. The issue of aspect dependency, algorithm development, and real-time operation leaves open to question the stepped frequency approach as a useful technique for mobile tactical radar applications.

The desire for rapid assessment of target features can most readily be met by short time measurement and high resolution of diverse target discriminants. This technique implies coherent processing of instantaneous wideband amplitude and phase information, using orthogonally polarized transmit vectors. Substantial work must be done to evaluate these techniques as to their effectiveness, and to develop hardware and software parameters prior to implementation. Although this approach has the most inherent promise in meeting the desired long term target recognition objectives, it is problematical that the required technology and field evaluation testing will surface in time to meet a post-1985 deployment schedule.

4.7 WAVEFORM SELECTION SUMMARY

Waveform selection is based upon spectral filtering requirements, system design constraints, and equipment cost considerations.

A simplified block diagram of the adaptive waveform process is shown in the Figure. The waveform that is transmitted is selected on the basis of the environment being searched, with inputs to the waveform control function from the environment map, antenna beam position, and range gate position. The transmitted signal is operated upon by the environment scattering function which can also include a target operator. The waveform process then consists of applying receiver weighting functions which maximize the target-to-interference ratio relative to the detection criteria. Upon detection, target 3D parameters are extracted for display and for system application. From an advanced technology viewpoint, the waveform process function becomes the major problem area both in terms of developing components for high speed processor architecture, and in evolving techniques for special applications such as LPI and target recognition.

The issues involving both inter-pulse and intra-pulse waveform selection are summarized in this section.

Preliminary Waveform Selection Criteria

Primary emphasis was placed on meeting the basic requirements for long range target detection in search, where methods noted in Barton[1] were utilized for initial sizing of system performance. The requirements were divided into two broad categories; the more typical environments of clutter and ECM (chaff/SOJ), and the special applications involving low probability of intercept (LPI) and target recognition. Investigation of the typical environment yielded two standard radar parameters for consideration; namely, the average power aperture product ($P_{AV}\ A_R$), and the processing bandwidth times the realizable MTI improvement factor (BI). The special applications requirements involved consideration of the radar processing gain and of very high range and/or Doppler resolution waveforms. These issues will now be considered in terms of the waveform interpulse and intrapulse characteristics.

Typical Environment

It was found in Section 4.1 that the search requirement in a clear environment (receiver noise only) could be met with a $P_{AV}\ A_R$ of 38 x 10^3. With other system considerations restricting the size of the effective antenna aperture to $8m^2$, the required P_{AV} computes to nominally 5 kW. This value of P_{AV} is noted to be independent of the type of modulation used in the radar waveform.

A first cut at the baseline radar waveform structure was then obtained by considering various other system requirements. Use of a solid state transmitter places restrictions upon the

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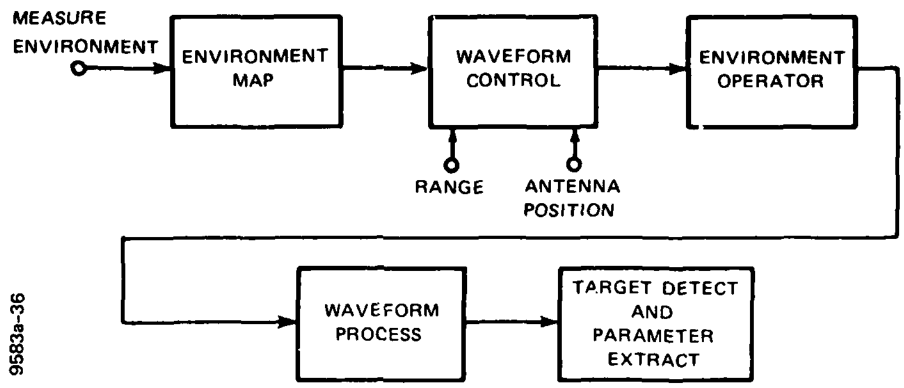
[1] Ibid, Section 4.1



Radar search waveform process

FIGURE A

pulse duty cycle to 10 percent or greater. This factor coupled with a prf of 400 Hz (200 nmi unambiguous range), results in a pulsewidth of at least 250 μsec. At this value, the peak power must be no greater than 50 kW for a P_{AV} of 5 kW. Utilization of a 250 μsec pulsewidth imposes first order constraints upon the waveform time-bandwidth product (TB). The value of TB now becomes a function of the required range resolution; where, as noted below, the pacing requirement is a consequence of clutter processing.

Clutter Processing Considerations

For basic 3D unambiguous long range detection, there is no stipulated requirement for Doppler resolution. Since the optimal design of the radar waveform is dictated by the inherent limitations on resolution performance, the absence of a Doppler requirement in search removes a significant level of complication. The requirement for range resolution is governed by height accuracy considerations and by typical plan view specifications; for example, resolving two targets spaced 1.5 nmi in plan position, 80 percent of the time. Such specifications can easily be met with a 1 μsec range resolution. Given the baseline constraint of a nominal 250 μsec pulsewidth, the clear environment TB product would be in the order of 250.

The demands of clutter processing, however, impose more restrictive bounds upon the processing bandwidth, which then directly affects the required value of the TB product. Clutter processing also directly influences the inter-pulse waveform design in terms of the degree of spectral filtering required. As noted previously in the waveform design section, there will be essentially three basic interpulse signals transmitted to meet the demands of the typical environment. For standard operation in the clear with close-in ground clutter, the baseline scan program described in Section 3.5.2 would be utilized with a 400 Hz prf. With rain clutter, the transmit polarization is switched to circular (or near-circular elliptical), and an 8-pulse sequence utilized at the 400 Hz prf. With chaff, a 2-stagger 8-pulse sequence would be transmitted at a 1600 Hz prf. Processing of both rain and chaff clutter can be further enhanced by transmitting an adaptively polarized waveform, which could lead to savings in processor architecture through a reduction of both the processing speed and the required TB Product. An additional receiving and processing channel would be required for parallel processing of the orthogonally polarized components of the target and clutter returns. This cost must be weighed against that of the higher speed, single channel processor, and would be a subject for further study.

The more immediate issue which must be resolved is whether adaptive polarization processing can actually realize the 5–10 dB of improvement needed to significantly reduce the processing bandwidth. This improvement is particularly required in the chaff environment which has the added dimension of ground clutter foldover. Additional study must be undertaken to determine these issues utilizing available models of typical targets and chaff corridors.

Processing of rain clutter imposes an upper limit upon the required TB product for conventional single channel operation with CP. The baseline rain processing bandwidth of 7 MHz, coupled with a 250 μsec pulse width, yields a TB of 1750. Although chaff processing is at the higher rate of 13 MHz, it is noted that the transmitted pulse width is reduced to 62.5 μsec, yielding a TB of 800. This reduction in pulse width is a consequence of increasing the prf to 1600 Hz, while maintaining the duty ratio at 10 percent for 50 kW of peak power. The chaff processing also requires bimodal filtering of ground clutter foldover, with an attendant 53 dB of clutter-to-receiver noise ratio. Preliminary sizing of the processor architecture was made for comparison of the rain and chaff configurations. A second estimate was made at a more moderate processing bandwidth of nominally 2 MHz, assuming that adaptive polarization processing gain could be traded against processing bandwidth. (See Section 6.4 for details).

Intra-Pulse Considerations

The preceding discussion was centered on the interpulse waveform characteristics, and on the time-bandwidth products associated with the necessity for coded pulse compression signals. Since resolution in Doppler is not required for the search mode, the intrapulse waveform selection is essentially governed by equipment considerations. The specific waveform should be chosen so that the performance requirements can be met with the lowest cost in system complexity.

The general classes of linear FM (LFM) and bi-phase coded signals (BPC) would be applicable as modulation techniques for the baseline waveform, realizing that there are many variants within these classes that could be considered. A key factor in the intrapulse waveform selection is the interference due to strong targets, which translates into some value of allowable peak range sidelobe level for the ambiguity function. An estimate of the acceptable peak sidelobes would have to be based on the number of interfering targets, number of peak sidelobes, target statistics, false alarm rate, etc. Since the TB product must be in the order of 1,000 2,000 for operation in rain/chaff, conventional bi-phase codes can be configured with peak sidelobes down by at least 30 dB. Rudimentary Taylor weighting can realize -35 dB sidelobe levels for LFM. At this juncture, it will be assumed that either waveform has an acceptable peak sidelobe response. Operation in a distributed clutter environment should also be consistent with the TB product utilized.

Initial processor sizing described in Section 6.4, was estimated using a bi-phase coded waveform with a hard limiting CFAR. The ultimate selection of the intrapulse waveform should be deferred until after extensive cost/benefit trade studies are made relative to system operation. Some key trade issues related to existing BPC and LFM technology are summarized below:

a) The BPC waveform, operating within the relatively long pulse of 250 μsec, requires 21 parallel Doppler channels to accommodate the loss in response associated with high speed targets at C-Band. On the other hand, there is now available a coarse estimate of target Doppler.

b) While LFM does not suffer any loss in response with target Doppler, there can be a maximum time shift of 1 μsec at Mach 3 speeds. This error in range was assumed acceptable, however, in search; and could be partially corrected in track. There may also be occasional masking by other targets in the beam caused by the range-Doppler coupled response.

c) BPC implementation is more amenable to existing baseband digital technology for the TB products required, whereas the LFM pulse compression may be constrained to IF. This latter consideration may impose additional dynamic range problems with LFM, if pulse compression precedes spectral filtering.

d) If target detection in a dense multiple target environment is a major consideration, then additional study should be undertaken to determine the performance lev . for both waveforms.

The chaff corridor described in Section 5 may contain targets spaced by 4 nmi or less. The 250 μsec pulse spans about 20 nmi. With a 4 nmi spacing, there will be an uncompressed code overlap of 80 percent between contiguous targets, and an average of five targets within the 250 μsec pulse. The effect of the sidelobe structure should be examined in relation to the desired false alarm and detection criteria. The problem may be more severe with the use of hard limiting CFAR with either waveform. With substantial code overlap and targets of differing cross section, the suppression effects of the strong signal can cause the detection probability of the weak signal to deteriorate rapidly.

In summary, the intrapulse waveform selection should be based primarily on equipment considerations and system complexity, noting that standard type modulation such as *linear FM and bi-phase switching may be acceptable.* Additional study relating to the above issues and to the expected component technology must be undertaken. System tradeoffs must also be considered, and these will be addressed in Section 4.8.

Special Applications – LPI and Target Recognition

As noted in Section 5.5, the LPI signal requires a high TB product; much more than that required for clutter processing. Long pulse durations approaching CW in the limit, are more effective than high or moderate pulsed peak power transmissions. LPI, therefore, is very amenable to solid state power devices. The basic problem is that intercept receiver technology may, in the post-1985 period, force the required LPI waveform TB requirement to the order of 60 dB. As a result, it is doubtful that the waveform generation and processing of high TB wide pulse signals will be cost effective, relative to that required for just meeting the performance levels in the typical environment. Unless there is some significant breakthrough in high speed gigabit type components and/or in code generation techniques, the strategy for countering the ARM threat would probably involve other ECCM techniques such as EMCON and decoys instead of total reliance on LPI.

The other special application deals with waveforms for noncooperative target recognition. Here, the ultimate requirement would be for extremely high range resolution from which to construct a two-dimensional target image. The high speed processing

technology and mass memory techniques, within tactical and cost constraints, may not be available until sometime after 1985. A wideband signal composed of narrowband frequency steps represents a possible interim system, but may involve observation times that are too great for a real time application.

One of the more promising systems involves the coherent processing of amplitude and phase of an instantaneous wideband signal (order of 200–300 MHz), coupled with polarization processing as an added discriminant. In general, the more discriminants available in the measurement, the less complex the recognition algorithm. Waveforms and real-time algorithms must be developed for the processing of target signature data. Much more extensive effort is required in this general area before any hard- and software implementations can be considered. An educated guess, however, would foresee the need for efficient short pulse high peak power transmitting devices, to avoid association problems with the signature return caused by the changing aspect of a high speed maneuvering target, and to reduce the time on target required to make an identification. Consideration should be given to design new radar systems with the instantaneous wideband and polarization agile capability, such that the target recognition function can be more readily incorporated at a later date.

4.8 WAVEFORM TECHNOLOGY FACTORS

Many investigations and tradeoff studies are indicated that are needed to meet, or improve on, the performance goals for the future ATR.

Examples of technology items include polarization processing, maximum entropy spectral estimation, and within-the-pulse Doppler processing. Their utilization would be examined within the basic constraints of the baseline design. Table I provides a list of baseline system technology items as they apply to the various operational environments.

While advances in component technology should lead to smaller and more efficient signal processor configurations, the escalating demands for multi-function operation generally force the size, weight, and power consumption to unacceptable levels. It then becomes incumbent to search for alternate means of processor implementation to reduce cost. Within the context of waveform technology, there are various areas for baseline system trade studies.

Dual channel polarization processing represents a major trade issue in this regard. Table II indicates the significant savings in processor complexity which can result from a reduction in the processor speed requirements, made possible through polarization enhancement of the target-to-clutter ratio. Other more fundamental trade studies involve spectral filtering utilizing maximum entropy techniques, range ambiguous prf, and within-the-pulse doppler processing. Transmitter duty cycle reduction can also result in a decreased processing requirement since the narrower pulse width involves a smaller time-bandwidth product. The trade issues here involve solid-state and tube type transmitter cost/performance versus processor cost. These various trade studies are summarized below in terms of technical risk and scheduling.

Dual Channel Processing

Dual channel polarization processing is a technique which can take advantage of the differences in the scattering properties between targets and clutter, such that one can maximize the probability of target detection. This approach is detailed in RADC[1978][1] and RADC[1979].[2]

Before any definitive system configuration can be finalized, the following technological issues must be resolved:

a) The dB improvement in target detection for dual channel rain/chaff environments relative to conventional single channel operation (includes circular polarization in rain).

b) Cost of dual vs. single channel antenna/receiver/signal processor.

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[1] RADC[1978] Final Report, "Implementation Techniques for Polarization Control for ECCM," Contract No. F-30602-77-C-0087, Oct. 1978, B035618L.

[2] RADC[1979] Final Report, "Polarization Processing Techniques Study," Contract No. F-30602-78-C-0119, Mar. 1979, A080565.

Table I. Baseline System Technology

Environment	Requirement	Baseline System Technology Trade Studies
Clear	$P_{AV}A_R > 4 \times 10^4$	• Tube vs solid-state transmitter for reduced duty cycle operation
		• Polarization enhancement
Ground clutter	$BI > 100$ dB-Hz $TB > 750$	• Polarization sensitivity
Rain	$BI > 92$ dB Hz	• Dual channel implementation
	$TB > 1750$	• Processor architecture, dual vs single channel
		• Ambiguous range prf
		• Spectral estimation
Chaff	$BI > 95$ dB-Hz	• Same as rain
	$TB > 800$	• Wideband processing
		• Within pulse Doppler processing
		• Code Diversity
Standoff Barrage	$P_{AV} > 5$ kW	• Dual channel processing
Jamming	$B_J > 100$ MHz	• Burn through capability
		• Sidelobe canceller
		• Adaptive sidelobe null
		• Jam strobe triangulation
Low Probability	Noise-like waveform	• Signature randomization
Intercept	$TB > 45$ dB	• Code development
Target Recognition	Short pulse High Peak Power	• Narrowband noncoherent
		• Narrowband coherent
	$B \sim 300$ MHz	• Instantaneous wideband – Phase – Polarization

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Table II. Processor Size/Power Estimate

		Single Channel Baseline	Dual Channel Matrix	2 MHz Dual Channel Matrix
SIGNAL PROCESSOR	Volume (ft^3)	58.8	122.0	28.8
	Power (kW)	11.0	22.9	5.4
DATA PROCESSOR	Volume (ft^3)	13.2	14.8	14.8
	Power (kW)	2.5	2.8	2.8

c) Polarization effects of ground clutter in bimodal situations.

d) Real time measurement of clutter scattering properties from which to determine optimum waveform. Utilization of more efficient estimation techniques such as maximum entropy methods should be investigated.

e) Cost/benefits of reduction in processing bandwidth resulting from dual channel enhancement of target detection.

f) Ancillary benefits from potential target cross-section enhancement in a clear environment, and similar benefits against noise jamming.

The groundwork for the above trade studies exists in the availability of a polarization processing approach toward maximizing target detection in clutter, and in the necessary software including target and clutter models to evaluate all of these items by computer simulation (see RADC [1979]).[1] The risk is, therefore, minimal in determining the cost/benefits derivable from a dual channel processing scheme, and could be accomplished within a one-year study effort.

Given that the study results are positive, then a much more extensive test program would be necessary to evaluate the system in a field environment. This program would involve development of critical hardware/software modules for incorporation into an existing radar test bed, with flight testing through both rain and chaff. Details of such a polarization processing test effort can be found in RADC (1978).[2] The cost of such an undertaking could be relatively high, including the requirements for flight test facilities, chaff drops, instrumentation, data reduction, etc. A rough estimate would indicate a 2-3 year effort. This program must be accomplished in a timely fashion if dual channel processing were to be incorporated into a post-1985 design. The technical risk would be considered low-to-moderate, since the field test effort would not be undertaken unless the results of the prior study indicated a very favorable cost/benefit tradeoff.

Spectral Filtering

Detection at long range is aggravated by the shear effects of rain/chaff, where the spectral spread of the clutter occupies all or a substantial portion of the relatively low prf region. As described in Section 4, relative to chaff processing, a higher range ambiguous prf permits enhanced spectral discrimination against the chaff. The situation is now aggravated by the attendant foldover of high levels of ground clutter. However, this can be compensated through utilization of adaptive, near-optimum filter banks, such that the baseline system is capable of meeting the search requirements in volumetric clutter.

There is, however, need for a more extensive baseline trade study in the general area of spectral filtering to upgrade performance. Better use of Doppler information would permit either a reduction in processor cost or operational capability in more dense clutter environments. The following technological issues would be appropriate for further study:

[1,2] Ibid. Section 4.8

a) Adaptive higher prf (to enhance spectral filtering) as a function of volume clutter extent, including effects of higher levels of ground clutter, bimodal effects with rain, and second time around volume clutter.

b) Adaptive antenna beam forming and sidelobe placement to reduce ground clutter intake.

c) Utilization of maximum entropy techniques for spectral estimation of the clutter for purposes of determining near optimum filter weighting.

d) Use of maximum entropy methods for possible enhanced spectral filtering relative to near oj timum filter bank, emphasis on real time operation with limited number of data samples.

e) Potential application of within the pulse Doppler processing in track mode.

f) Very high prf (pulse Doppler) application in track mode, including potential for high Doppler resolution.

The above would be a low risk study effort of 3-6 months duration.

Duty Cycle Trade Issues

The transmitter pulsewidth has a pronounced effect upon processor cost related to the required value of the waveform time-bandwidth product (TB). Since there is no requirement for Doppler resolution in search, the pulsewidth utilized is determined primarily by transmitter design factors. The solid state baseline transmitter design constrains the pulsewidth to at least 250 μsec at a prf of 400 Hz because of peak power limitations. The pulsewidth can shrink, however, proportionately to higher range ambiguous prf's as in the case of chaff processing.

The disadvantages of 'wide' pulses are:

a) For required processing bandwidth, have high TB product with increased processor complexity.

b) Require additional parallel Doppler channels for bi-phase coded pulse compression.

c) Increase uncertainty of range measurement for linear FM waveforms.

d) Degrade operation in dense multiple target environments.

The advantages of a wide pulse are:

a) Permit increased Doppler resolution.

b) Enhance low probability of waveform intercept.

c) Enhance two-dimensional radar imaging for target recognition.

On balance, a qualitative assessment of advantages and disadvantages would mitigate against the use of a very wide pulse. This judgement is based primarily upon signal processor cost for operation in the typical threat environment, whereas the advantages apply principally to the more special applications. Therefore, the following trade studies would be appropriate:

a) Processor cost as a function of pulse width for typical waveforms such as linear FM and bi-phase codes.

b) Effect of pulsewidth and TB product upon operation in multiple target environment, including effects of range sidelobes for both linear and hard limiting CFAR, effects of large-to-small target ratios.

c) Effects of pulsewidth and duty cycle upon transmitter design, tradeoff cost/ reliability, etc. between solid state and tube type transmitters.

The above is a low risk study effort, estimated 6 months duration.

Wideband Processing in Clutter

The need for processing of instantaneous wideband signals has been discussed in the sections dealing with low probability of intercept and target recognition waveforms. The trade studies in these areas are very specialized, and it is recognized that there is a need for continuing study both in the systems and components disciplines. Within the confines of the baseline system, wideband processing is of more immediate interest in the detection of very small cross section targets in clutter. The trade study issues involve the distributed nature of the range spread target scatterers, and the effect upon false alarm and detection criteria in the various clutter environments. Some typical tradeoffs would include:

a) Optimum choice of range cell size and effects of nonoptimum cell size upon performance in volume and area clutter.

b) Processor configurations, including coherent, noncoherent, parallel and sequential observations.

c) Trade between instantaneous coherent use of wideband signal and noncoherent frequency hop approach.

This is estimated as a 6-month study effort including a survey of available literature on this subject.

Section 5

TRACKING TECHNOLOGY

5. TRACKING TECHNOLOGY

5.1 AUTO TRACK FUNCTION

Because the radar is a significant element in the sensor arsenal of the TAC AFFOR Commander, the ATR must be able to extract, track and classify targets.

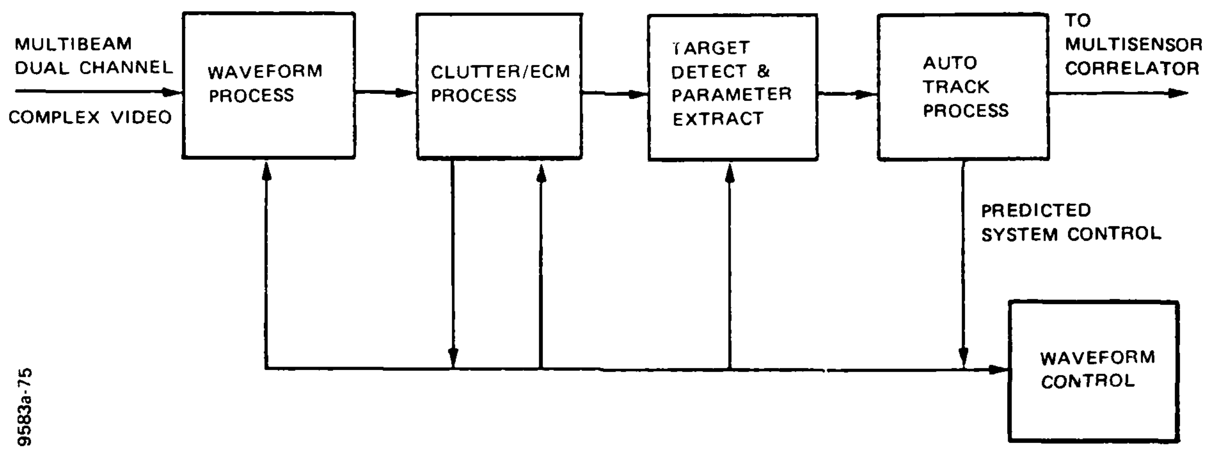
The operational and threat environment issues addressed elsewhere in this report have emphasized the need that the system must: (1) achieve a high level of automaticity, (2) possess a capability for adaptive resource management, and (3) capitalize on the synergism realized from netting of the system's sensors to obtain fast reaction to a multiplicity of threats.

The main theme stressed in this approach is that target data and environment data are used to continuously configure the system into a format which optimizes target extraction, target track, and target classification. In this manner, the processing resources are always balanced so that excessive demands will not have to be made on the performance measures of any one subsystem. A balanced approach to single radar sensor control is illustrated in the accompanying Figure. This ties together the previously discussed functions of waveform and clutter/ECM processes and target detection and parameter extraction, with the autotrack process. Although each function must be satisfied in the sequence shown prior to developing an automatic track, a key fact noted in the Figure is that the operation of the autotrack process feeds back and directly impacts the operation of all of the other processes.

The other critical aspect of the autotrack process is that its output represents the major radar sensor data interface with the tactical user. As such, an ancillary theme to the above is that single system tracks (SST) have to be established and identification determined using all target data derived from all sensors in a timely fashion. The netting or merging of target data is the final operation upon which the tactical user depends. The radar is a significant element for target verification from which the TAC AFFOR Commander will base his battle decisions. To maximize the timeliness and value of the assimilated information, the sensors must provide target information filtered, identified and merged to the maximum degree available. Target track data, with all available correlated cooperative and noncooperative identification information incorporated, will minimize the data transmission and central processing load as well as increase effectivity of the system. Toward this end, the SST requirements must be responsive to:

Optimum Control of Sensor Resources
Low False Track Rate
High Track Solidarity
Fast Reaction Time
Automatic Threat Assessment
Large Track Capacity
Optimum Merging of Sensor Data
ECM Resistant

The issue of optimum energy/resources control becomes especially crucial for multifunction radar use embodying both search and track. For the baseline design,



Balanced approach to radar control

prf of 400 Hz in a clutter environment, extraction of angle data with sequential lobing can utilize as much as 80 μsec or more per target. Assuming that only two seconds per search interval is allocated to track data update, then only 25 targets per antenna face can be accommodated. From the tactical user viewpoint, timely assessment of the threat is fundamental to the optimum allocation of limited weapon resources, in a major hostile engagement. The issue of target classification is highlighted in Section 5.8 and represents one of the more crucial outputs of the autotrack process. In effect, the level of automaticity realizable is critically dependent on the efficacy of the target classification function. If the variances associated with the target classification outputs are minimal, then a high level of automaticity is feasible resulting in decreased system reaction time. However, a critical facet that impacts the efficacy of the target classification function is the degree of adaptiveness that the surveillance radar possesses (e.g., variable track verification data rates).

It is essential, therefore, that track initiation be accomplished with a minimum of "looks" per target, and that false or redundant tracks be minimized. This can be facilitated by proper distribution of false return rejection among the various radar processes, and the utilization of special wideband waveform modes to enhance the classification of targets of interest. This will be adaptively controlled by tracker feedback in predicted target areas. The above represents major technology radar design trade issues, which will be expanded upon in the following topics.

Although balanced radar sensor design can provide a cost-effective mechanization for track while scan operation, the varied nature and magnitude of the threat presages the necessity for a multisensor network. The benefits to be realized from sensor integration are: (1) reduced ECM susceptibilities and vulnerabilities, (2) higher data rates for system track accuracy, (3) lower (and nonperiodic) data rates for effective anti-ARM countermeasures. (4) increased system track continuity in the presence of multipath or scintillation induced fades or natural masks, (5) greater trajectory following capability, (6) jammer range determination when jammers are beyond the system's burnthrough detection range, and (7) faster track establishment times.

The requirement for a multisensor adaptive system tracker poses additional technology trade study possibilities regarding techniques for optimally combining the outputs of the individual radar sensors. The mechanization of a system track function will influence the design of the local track process, which, as noted before, has an iterative effect upon the balanced design of the other radar processes. Consequently, the design approach for the system tracker will have major impact upon the requirements and costs of the individual radar (i.e., possible utilization of less than four antenna faces per sensor).

Since the technology for adaptive system track functions has not as yet been developed in terms of a formalized methodology, this feature ranks high in the evolution of the advanced tactical radar system. A discussion of the above design methodology and associated parametric trade study requirements is, therefore, presented in the next topic.

5.2 MULTIPLE SENSOR NETTING

One of the most important features of the future Tactical Air Control System (TACS) is the netting or integration of many radars to produce a single system track for each target within the coverage volume.

The synergism resulting from the joint action of multiple sensors is needed to cope with the very severe threat environment envisioned for the system. Some of the benefits that will be realized from sensor integration are:

- Increased system track accuracy
- Faster track establishment time
- Increased system track continuity
- Reduced ECM susceptibilities
- Reduced number of false and redundant system tracks
- Greater trajectory following capability
- Enhanced threat classification capability.

The success with which the system track function performs also affects the required performance level and/or cost of the individual radar sensors. In an advanced TACS, rapid automatic threat assessment is a major consideration for the management of sensor resources. For example, utilization of the baseline agile scan antenna allows multiple extractions to be made on high priority targets by revisiting selected points during a single scan period, enabling faster track verification and target classification. The allocation of individual sensor resources on a system basis can alleviate the average power constraints, low prf requirements, and fixed antenna face operation of the baseline design. Single sensor energy can be concentrated in regions that demand track of multiple targets with high update rates, which would normally be limited by the 2.5 msec pulse repetition interval and the demands of the search function. The latter can be temporarily allocated to other radar sensors. Individual sensor design may also be practicable with less than four fixed antenna faces per radar, depending upon total coverage afforded by the collective network. The ability to alleviate the demands placed upon the resources of individual sensors, will be directly related to the efficiency with which the Single System Tracker can be designed. This issue is detailed below.

The key to the success of sensor integration is the degree of accuracy improvement achieved. If little or no accuracy improvement is gained, then many of the benefits of netting will not be realized since the accuracy of the system tracker affects the performance and operation of all the tracking processes. Track continuity, for example, is directly dependent on the state estimator's ability to provide accurate predictions and to accurately detect changes in the target state. The prediction information and target state changes are used to select the optimal gate sizes for track association. If the information is inaccurate then the chance for misassociations increases, thereby affecting track continuity and ultimately the system accuracy.

The users of the ATR surveillance net will commit their resources based on tracker information and, as such, the multisensor adaptive system tracker is the primary determinant of the ATR network performance. To ensure optimal allocation of resources, the tactical decision maker must be presented with an accurate, timely, reliable, and complete description of the total tactical situation that is devoid of any data that confuses or does not contribute to his assessment of the situation. Therefore, the objective of the multisensor adaptive system tracker is to extract an accurate, user surveillance-oriented description of all real targets of interest while suppressing false reports and reports on targets of no interest. Furthermore the user is interested in the time history of detections or, in other words, tracks.

Very little work has been done towards developing a cost-effective multisensor adaptive system tracker that can handle the total threat population faced by a tactical surveillance radar network.

The following sections outline and elaborate on the major tracking technology issues associated with the multisensor adaptive tracker, which is the keystone for a cost effective integrated ATR system.

5.3 DATA INTEGRATION

In order to achieve the accuracy enhancement resulting from sensor integration, a trade-off analysis is required to ascertain the best way to combine or select sensor data for the system tracker.

The basic data integration problem is illustrated in Figure A. The set of sensors may be the same (homogeneous), i.e., all 3D ATR systems, or they may be a mix of 2D, 3D, or multistatic sensors. For the general case of multiple sensors, the radars may be spatially separated by large distances (miles) or they may be co-located within a few feet. Also the data rates may or may not be synchronous. For a set of ATR's, the network would most likely consist of spatially separated systems. If other types of surveillance radars are brought into the net, then there is a chance that an ATR may be co-located with a long range 2D radar. As a result the effects of both co-located and spatially separated radars must be considered in the design of a system tracker.

The fundamental problem is then to determine the best way to combine or select detections and/or tracks prior to processing by the System Tracker so that the maximum accuracy is obtained for all possible target states. A few of the system tracker input alternatives are shown in Figure B for the simple case of two sensors.

The advantage of combining equal variance, σ_S^2 data samples from two or more independent sources is easy to see since estimation theory states that the resultant variance, σ_T, is σ_S^2 divided by the number of sources. This method of combining data, however, does not account for data arrival time; it presupposes that time has no effect on variance reduction. Analyses must be done to determine whether data arrival time, which may be periodic or random, has a significant impact on obtaining accuracy improvements sufficient to justify combining data.

Under certain conditions it may be better to just select the most accurate radar. Combining good data with very bad data would yield no improvement in accuracy and would use very valuable processing time needlessly. The questions that must be answered, however, are when does one combine or select data and where is the dividing line between the two?

The siting problem becomes an issue in the ATR systems since they are mobile and quickly moved to new sites. For an ATR surveillance net when the radars are spatially separated by relatively large distances such that the radar coverage profiles are restricted by shadowing and noncomplimentary fields of view, then the optimal data combining method may be track-to-track. However, under some conditions detection-to-track may be better. The underlying issue here is the effect of the radar registration bias errors on the method of combining data. Again an optimization analysis must be done taking into account the registration errors.

In summary, the pacing problem with any automatic and adaptive multisensor system tracker is the method used to select or combine the data going into the tracker. The

solution to this problem will allow one to perform a military worth analysis on any multisensor configuration and decide the best methods for data selection or combining. In the process, since the methodology will be optimal, the design chosen will provide maximum performance with minimum processing cost.

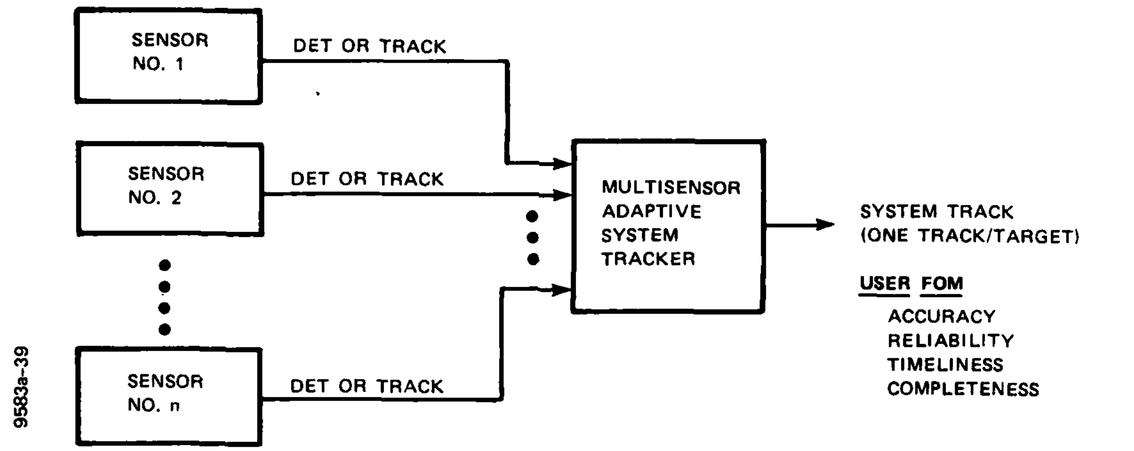


Figure A. Data integration is of prime importance in a multisensor system

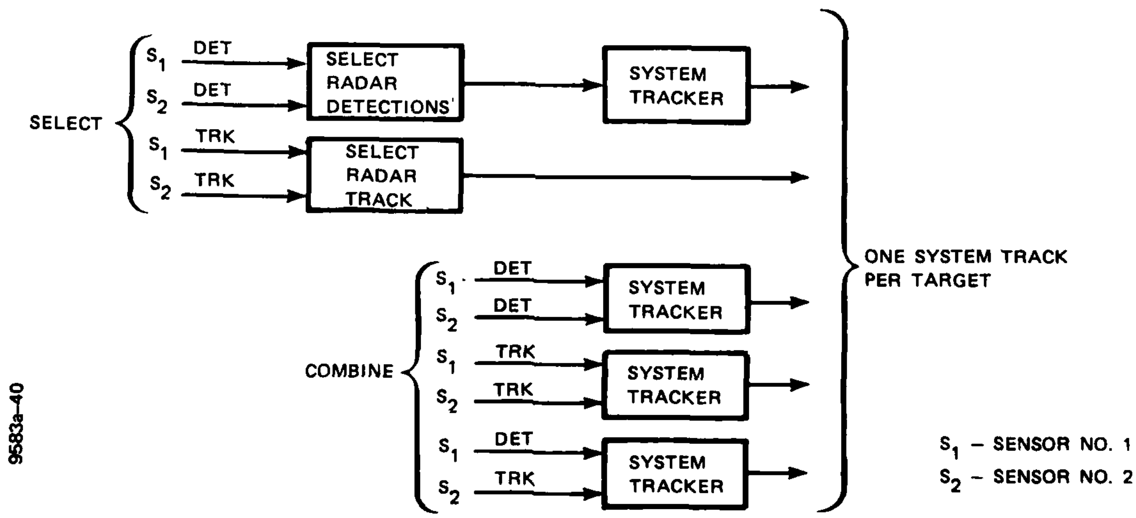


Figure B. Input alternatives for two sensors

5.4 SYSTEM TRACKER FIGURES OF MERIT

An important task in performing an operations analysis of the multisensor adaptive system tracker is that of defining the system figures of merit from the users point of view.

Generally the users of modern radar surveillance systems are interested in the information derived from the time history of detections (tracks). Such information addresses the target's position, velocity, course, etc. To assist the decision maker in optimal allocation of his resources, several features of the track are desirable:

- Speed at which tracks are formed
- Accuracy of the track
- Consistency of the track
- Track endurance
- Speed of track deletion when the track is no longer valid
- Freedom from false and redundant (two or more system tracks on the same target) tracks.

The system figures of merit must reflect these design characteristics in non-technical language that the user can understand. Furthermore, the design figures of merit for the entire multisensor tracking system must be related to and be expressible in terms of the system figures of merit.

An example would be the system figures of merits for a track-while-scan (TWS), 3D surveillance radar tracking system. They are:

- Accuracy
- Timeliness
- Reliability
- Completeness

A similar set of system figures of merit must be defined for the multisensor adaptive system tracker since the measures of effectiveness for any system are a function of the figures of merit.

5.5 TWS SURVEILLANCE TRACKING PROCESSES

Multisensor system accuracy is dependent upon the state estimation process in the system tracker.

There are six tracking processes within a modern TWS surveillance radar tracking system. The tracking processes, illustrated in the Figure are:

- Smoothing
- Prediction
- Coarse Association (Correlation)
- Fine Association
- Track Initiation
- Track Deletion

The keystone to the entire tracking system is the state estimator, which includes the smoother and predictor. Ideally, the total surveillance description presented by the tracker should describe the target states with infinite precision and have zero delay. Because of several factors such as target (state) noise and measurement errors of the sensors, the ideal description is unattainable; it can only be approached in a physically realizable design. One such design is the Best Linear Unbiased Estimator (BLUE) tracker: A tracker whose tracking gains are optimal and adapted on every update, and, further, a tracker that can handle variable update rates.

When compared with classical tracker designs, the adaptive BLUE tracker offers a severalfold increase in smoothing and prediction performance because it has:

a) Minimum transient response (a critical factor for low flying threats)

b) Adaptivity to changes in the environment and threat tactical variables (maneuver following and missed detections)

c) High system accuracy for the total track population (primary figure of merit for state estimation)

The last attribute distinguishes the adaptive BLUE tracker from other optimization criteria that have been used in designing tracking systems. For example, trackers have been designed that are optimum for constant velocity targets, constant acceleration targets, or specialized targets such as tactical ballistic missiles. These criteria are generally valid for single fire control units where a one-on-one situation exists. An assessment of the tactical situation, however, dictates that the total track population be presented with the highest precision possible. Surveillance radars therefore necessarily have tracking requirements that are quite different from those of fire control radars.

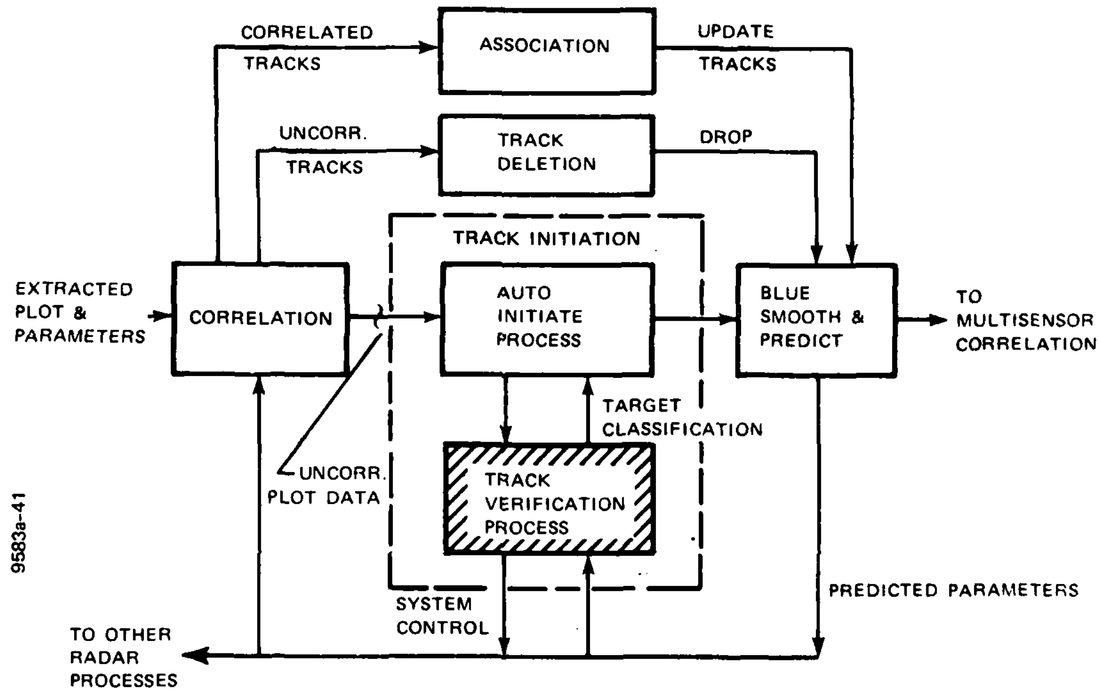
For very large track populations, it is not cost-effective in terms of time and/or memory to optimize each track. The BLUE methodology, therefore, accounts for the total population to produce a design that maximizes performance and minimizes processing cost.

The ultimate multisensor system accuracy will be determined by the state estimation process in the system tracker. The optimal state estimator may be designed using the BLUE methodology, but it must be preceded by an operations analysis to determine the best coordinate system, the threat mix and trajectories, the data rates, the order of the tracker and effects of the ECM environment.

One of the dominant issues here is the selection of the best coordinate system for the system tracker as well as the entire multisensor network. An additional consideration is the effect of radar registration bias errors on the final system accuracy, and whether the choice of coordinate system will further influence the registration errors.

Modern estimation theory indicates that the order of the state estimator should be matched to the order of the expected state variables, that is, the target dynamics. In Kalman Formalism then, the order of the known dynamics is modeled in the deterministic state representation and the uncertainty of the state order modeled in terms of state noise. Inasmuch as the order of the dynamics varies from one coordinate system to another, it is important to select the coordinate system that gives the lowest order. The lowest order not only simplifies the computational burden but more importantly it gives the greatest accuracy estimates. For example, a far greater position estimation error occurs when applying a third order tracker to a second order process than when applying a second order tracker to a third order process. Since most aircraft exhibit second order dynamics most of the time relative to the earth's tangent plane (excluding ballistic trajectories and evasive maneuvers), the problem is to develop a second order tracker that adaptively corrects for acceleration when higher order unknown dynamics are present.

Another important multisensor issue is the impact of the ECM environment on the state estimation and association processes. Noise jamming will increase the variance of the state estimates which in turn will affect the association gate size. This then requires that the state estimator be adaptive to large changes in the measurement noise and must further be able to detect these changes to that the association processes may also adapt to these changes.



Tracking processes used to correlate and estimate track position

5.6 ASSOCIATION AND AUTOINITIATION PROCESSES

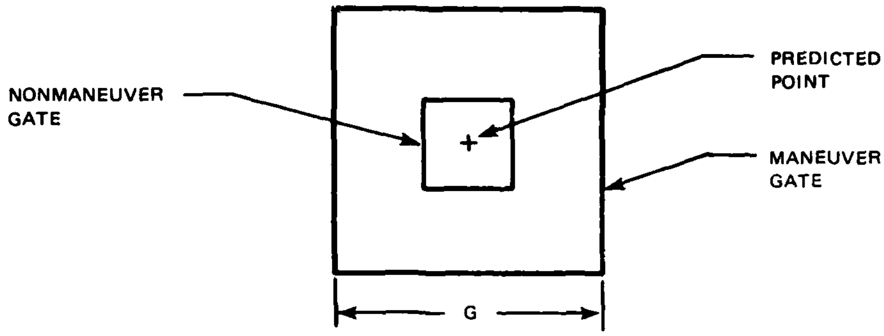
The association processes (also known as correlation and association) have a major influence on system tracker accuracy and reliability.

The state estimator is dependent upon the association processes providing it with the correct detection and track pairs during each track update. An incorrect pairing or a missed association would reduce the accuracy of the track. Therefore, an important design figure of merit for the association processes is track life. It is a measure of effectiveness that shows how well the association processes can correctly update a track without a miss. This then stipulates that the association processes must be adaptive to changes in the environment since radar measurement errors, tracker prediction accuracy, and the target dynamics are variable and not fixed. Furthermore, the association processes must also be adaptive to the clutter and ECM environment.

Just as the state estimator was dependent upon the association processes for correct detection and pairings, the association processes are in turn dependent upon the state estimator to provide accurate predictions, maneuver following information, and missed detection capability. The state estimator together with the association processes form a closed-loop system (known as the track update loop) that must be adaptive to changes in the environment. As in the case of the state estimator, the coordinate system will be critical in determining the optimal association gate size, shape, location, orientation, and numbers.

One of the primary design figures of merit for the association processes is the probability of correct association (PCA). To maximize this quantity, the association gate geometry must be such that it maximizes the probability of capturing the detection and, simultaneously, minimizes the probability of including false or unwanted reports. To achieve this the gate size, gate shape, orientation, and the location must be optimized for the selected coordinate system.

Other important issues include track resolution, track selection, false tracks, switched tracks, lost tracks, and missed tracks. Track resolution is especially important since the multi-sensor adaptive system tracker will determine the target resolution capability of the entire system. The technology issue involved here is the fine association process. Coarse association sorts detections in the radar coverage volume into optimal identification space. So long as there is only a single track and a single detection there is no problem in correctly associating the two. When there are multiple overlapping tracks with multiple detections, however, the fine association process is needed to select detections to match with each track. The problem is that an algorithm that can perform the correct pairing of detections to tracks in real time and on a tactical computer system does not exist. Further research is required in this area since the ability to resolve targets is dependent upon the fine association process.



$$G = C(\sigma_m{}^2 + \sigma_p{}^2)^{1/2} + M_1 + M_2$$

WHERE

G = GATE LENGTH

C = STATISTICAL CONSTANT

$\sigma_m{}^2$ = MEASUREMENT VARIANCE

$\sigma_p{}^2$ = PREDICTION VARIANCE

M_1 = MANEUVER VARIABLE

M_2 = MISSED DETECTION VARIABLE

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The basic association gate sizing equation used in the SEA design

An adaptive association algorithm known as SEA[1] (surveillance eclectic association) has been designed for use on a shipboard TWS 3D surveillance radar and is currently undergoing tests at a land based test site. The design is significant in that it is fully adaptive to the environment. The association gate size is adaptive to changes in the clutter environment, target state (maneuvers) and missed detections. The SEA algorithm operates in conjunction with the BLUE tracker to form an adaptive closed-loop track update loop.

The basic association gate sizing equation used in the SEA design is shown in Figure A. As can be seen, the gate is primarily affected by the radar measurement accuracy and the tracker prediction accuracy. For the multisensor case an additional error term will be included to account for sensor registration bias error. When the multisensor system is in an ECM environment, the increased variance caused by noise jamming will affect both the measurement accuracy and the prediction accuracy. The statistical constant is selected based on an operations analysis of the tracking environment and is used to adjust the gate size to balance performance requirements against computer processing cost. The maneuver following and missed detection terms are enabled only when the BLUE tracker has detected either a maneuver or a missed detection.

Increased performance demands on reaction time and clutter rejection capability have a direct effect on the track initiation process. For a high false track environment, a critical element of the system reaction time is the amount of time from initial detection of a target to firm track status. This time interval is called the track initiation time. The time required to initiate a track directly affects the rate at which false tracks are established and the probability that real target tracks are established.

Therefore, the basic tradeoff that must be made for the multisensor adaptive system tracker is between track initiation time and the rate at which false tracks are generated. In addition, since the threat, clutter, and ECM environment can vary widely, the track initiation and deletion processes must be adaptive to ensure that the system false track rate is maintained at a constant rate. Maintenance of a constant false track rate is an important figure of merit.

The track verification process is an important adjunct to the autoinitiate function. Reaction time can be shortened by utilizing target position, velocity, and acceleration data from the tracker state estimator. Other information, such as derived trajectory estimates and special application of wideband signature modes, can be utilized to further classify the target as a potential threat. The target classification function can then be used with the other track data to verify track and complete the autoinitiate process. Details of track verification are included in Section 5.7.

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[1]ITT-Gilfillan, SEA (V4879) Association Process for AN/SPS-48C, Contract N00024-77-C-7159. To be published.

5.7 TRACK TECHNOLOGY ASSESSMENT

There are issues in all six areas of the tracking process that must be developed in order to suitably perform the tracking function in the ATR.

The tracking technology discussion has focussed primarily on the issues confronting the design of a cost-effective multisensor adaptive system tracker. The major tasks that need to be performed to develop a methodology for multisensor adaptive system trackers are as follows:

- Perform operations analysis and develop performance figures of merit
- Perform data integration trade-offs
- Establish registration error budgets
- Coordinate system trade-off analysis
- State estimator optimization analysis
- Association optimization analysis
- Initiation and deletion optimization analysis
- Design computer simulations
- Perform cost-effectiveness trade-offs
- Perform military worth analysis
- Design system tracker
- Perform evaluation of system tracker.

The last five items are included to complete the process leading from operations analysis to an engineering design and the performance evaluation of that design. The complexity of the problems are such that computer simulations will be necessary to perform the operations and optimization analysis for each of the track functions. Additional computer simulations will be needed for the trade-off analyses and performance evaluations.

5.8 TARGET CLASSIFICATION

Target classification is an integral part of the track verification process and can be significantly enhanced through special waveform applications which provide wideband polarization sensitive target signatures.

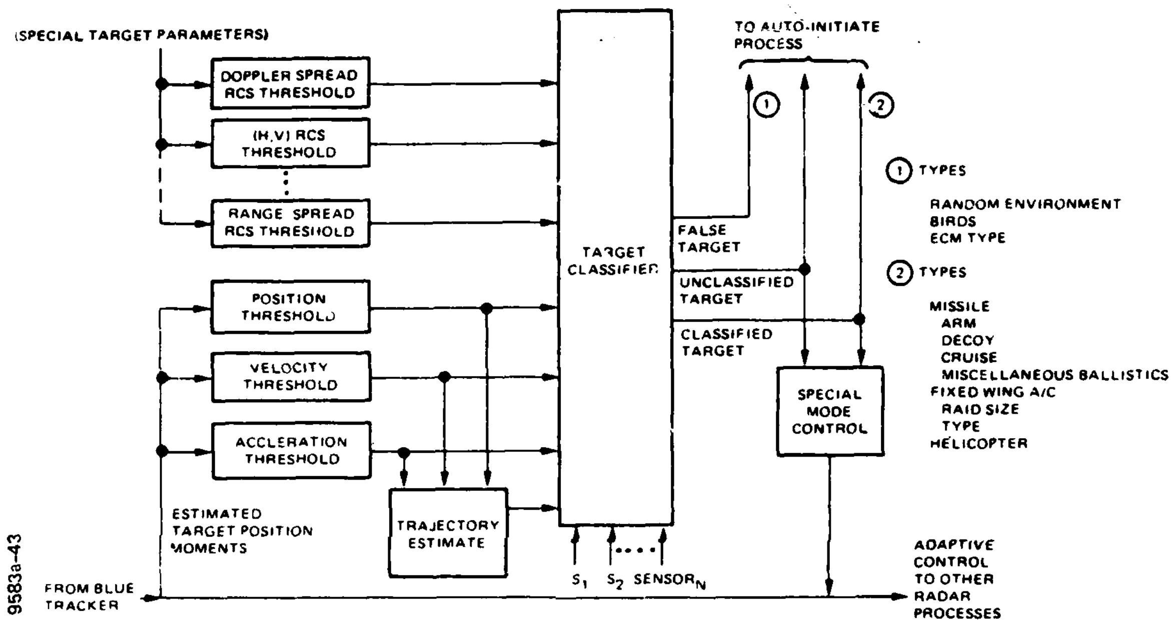
The need for rapid automatic assimilation of target data, both for single and multi-sensor system configurations, has been underscored in the previous topics detailing the operation of the track function. Target track data with all of the available correlated cooperative and non-cooperative identification information is essential to timely assessment of the threat environment. Target classification is an integral part of threat assessment, but functionally it is also part of the track verification process as shown in the Figure. The track verification process has a direct effect upon the probability of track initiation, the rate of false track initiation, and on the time to initiate track. During track initiation, the track verification process is utilized to establish the track in the most effective manner for a given target class.

As noted in the Figure, the target classifier function receives position, velocity, and acceleration estimates from the BLUE tracker function. These estimated target position moments are then operated upon to derive an estimate of the target trajectory, which is also input to the classifier function. These initial track parameters are then utilized during the autoinitiate process for special mode control of the waveform and signal processor functions. In particular, instantaneous wideband waveforms can be transmitted from which range-spread Doppler-spread, and polarization sensitive signatures can be obtained for selected initial target tracks. These special target parameters, noted in the Figure, can provide additional valuable information for a more rapid assessment of target class.

In a multi-sensor configuration, similar inputs from other radars in the network would be utilized to enhance the track verification process. Other data such as derived from IFF or JTIDS could also be utilized. Once the auto-initiate process has been established for a given target, the types of target classification information available would be as noted in the Figure. For threat evaluation purposes, the following data should then be available within the system:

1) Target Position
2) Target Velocity
3) Target Acceleration
4) Time at which data was valid
5) Confidence level for target parameters
6) Threat Assessment Factors, including derived target classification and raid size determination
7) Jam Strobe data
8) ECCM Status (on a sector-by-sector basis, including which anti-jam features the radar has automatically selected)
9) IFF/JTIDS data.

Although all of the items listed above are important for threat assessment, the remainder of Section 5 will be primarily concerned with the use of the special target parameters in determining target classification. This is occasioned by the fact that major technology emphasis will lie in the processing of polarization sensitive range/Doppler-spread signatures, and in the concomitant development of target classification algorithms.



Track verification process

5.9 WIDEBAND TARGET SIGNATURE CLASSIFICATION

A technology assessment of target classification utilizing instantaneous wideband signature responses shows sufficient promise for inclusion in a post-1985 multi-sensor radar network.

Non-cooperative target recognition was discussed in Section 4.6. It was noted that a post-1985 deployment schedule would be problematical in meeting the desired long term objectives for target recognition. This conclusion was based on the presumption that the target would be "precisely" identified as a BQM-34A drone, an F-4 fighter aircraft, etc. An interim solution can be achievable, however, by utilizing data obtained with an instantaneous wideband waveform as an adjunct to the track, jam strobe, and IFF/JTIDS information. This basic approach is shown in simplified form in Figure A.

Given that a preliminary track has been established on a target, the radar can, under the special track mode controls, transmit an instantaneous wideband waveform of nominally 200 to 300 MHz confined only to the track region of interest. The transmit-receive polarization states are also controlled to facilitate clutter processing and target discrimination. Wideband data would then be collected in a high speed memory which stores and processes data only in the 3D tracking gate. The collected wideband signature data can then be read out of a memory at a much slower speed to implement the signal processing functions of spectral filtering and pulse compression. The implementation of the latter two functions can be simplified by utilizing velocity estimates from the BLUE tracker.

The wideband target signature, track data, and other pertinent data would then be evaluated in a threat classification algorithm. The desired output would then be classified into one of several broad categories; for example, fighter aircraft, bomber, helicopter, missile, etc.

Utilization of high speed data collection over a limited range extent with the subsequent slower speed signal processing, is intended to accommodate existing and near term advances in component technology. These factors are discussed in Section 6.4.5. The remainder of this topic will be concerned with target classification trade study issues.

Target Classification Considerations

The approach to target classification suggested in Figure A, would involve utilizing polarized high slant range resolution target signature data. Representative data can be found in the final report on Tactical Aircraft Identification.[1] Several examples are noted in the accompanying figures as excerpted from the referenced report. The data shown were derived from polarization sensitive models of the BQM-34A target drone and the F-4 fighter aircraft. The computer outputs correspond to a frequency of 5500 MHz, with an instantaneous bandwidth of 320 MHz (range resolution of ≈ 0.45 meters). In these figures, the target radar cross-section is plotted as a function of slant range. Zero range corresponds to the target center-of-gravity, with negative range closest to the radar along the line-of-sight.

[1] Ibid, Section 4.6

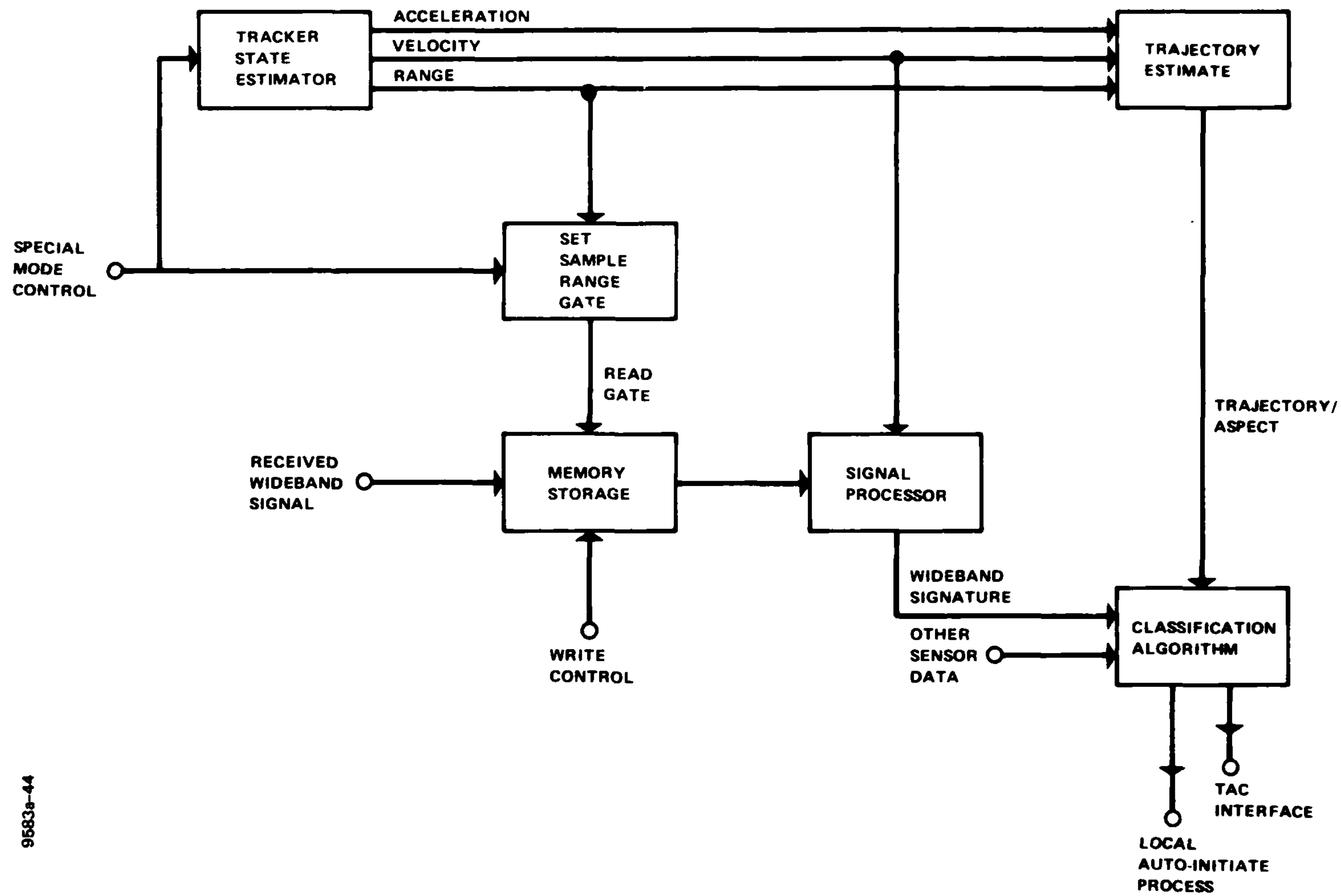


Figure A. Wideband classification process

Figures B, C, and D are cross-sectional cuts of the drone signature for a horizontally polarized radar. The cuts are at yaw angles of 0, 45 and 90 degrees respectively, holding the pitch and roll angles at zero degrees. Figure E shows a broadside view of the F-4, which is remarkably like that of the drone. The shape is wider (3 meters versus 1.2), and the cross-section amplitude is greater (9,000 versus 2,000 m^2).

This small sampling of high range resolution signatures highlights some of the problem areas inherent in the target classification process. For a given target, the dynamic range of scatterer cross-section is 30 to 50 dB. This can be even higher over an ensemble of targets. Another severe problem is the variation of the wideband signature with target aspect (pitch, roll, and yaw). To avoid smearing or distortion of the signature, the data collection should be accomplished over as short a time interval as possible. This is particularly true for maneuvering targets, and for high speed targets crossing the radar line-of-sight. In this regard, data collection utilizing instantaneous wideband signals is clearly superior to frequency stepped narrower band signals transmitted over the same total bandwidth.

The above issues, wide dynamic range of target scatterer cross-section and variation with aspect, present fundamental problems in hardware and algorithm development. Assume, for example, that it is required to distinguish 0.1 m^2 scatterers in the presence of receiver noise at a target range of 87.5 nmi. With the existing baseline parameters, there will be a 10 dB s/n ratio for the 0.1 m^2 cross-section. It is likely that 10 dB may not be adequate for providing the required degree of signature discrimination, noting also that many scatterers are less than 0.1 m^2. The resultant average transmitted power would then have to increase to more than 50 kW, pushing the peak power to better than 500 kW. Alternatively, the 5 kW waveform could be used with longer dwell on target for coherent integration of ten or more pulses. This would increase the data collection time to more than 25 msec, which may be too long in preventing signature smearing.

The above is further complicated in an ECM environment of jamming and/or chaff. Even moderate stand-off jamming may require a factor of two increase in available average power. The effects of chaff are reduced by the wide signal bandwidth, but this is nullified when the target aspect results in very small scatterer cross-sections. It is expected, however, that the velocity estimate provided by the tracker would significantly enhance spectral filtering of the chaff backscatter.

Another fundamental consideration is the sidelobe structure of the intrapulse coded waveform, as it relates both to the single and multiple target situations. Referring to the target signature profiles, it is noted that the variation in cross-section between scatterers can be more than 10 dB for a fixed target aspect. Consequently, the larger high resolution scatterer range sidelobes can interfere with and change the signature response within the smaller scatterer regions. The allowable degree of such interference remains to be determined. A rough estimate, however, indicates better than 30 dB down sidelobes would be required. The trade issue here would be the high peak power required and/or a long duration data collection.

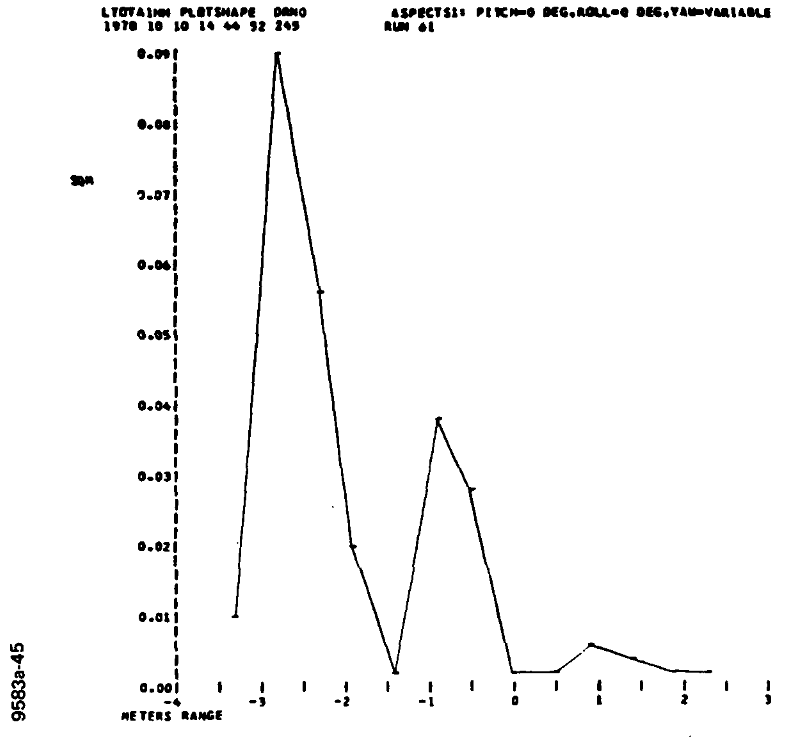


Figure B. BQM-34A, 0° yaw horizontally polarized radar signature

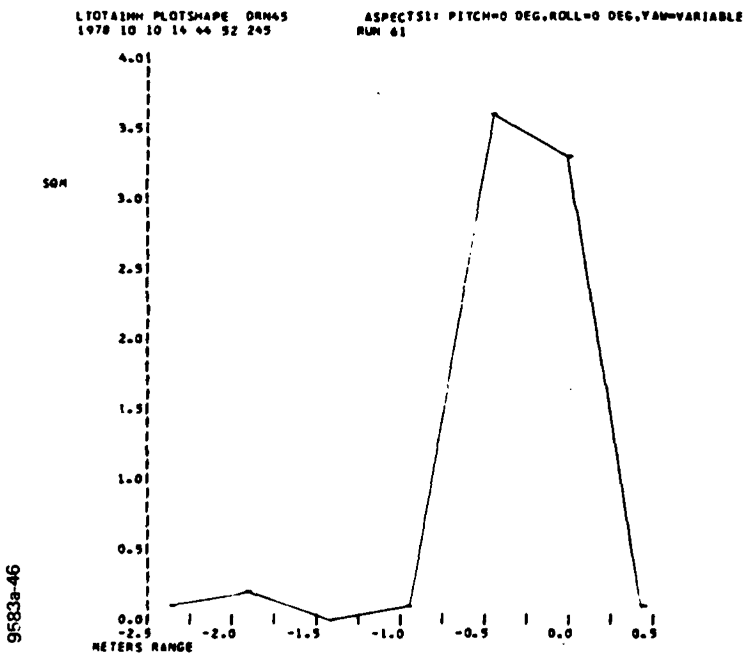


Figure C. BQM-34A, 45° yaw horizontally polarized radar signature

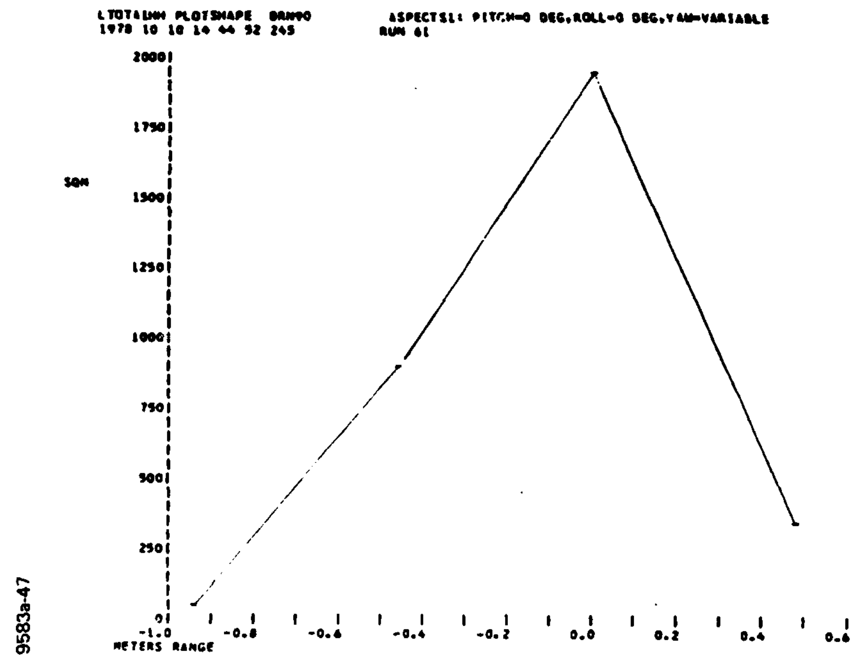


Figure D. BQM-34A, 90° yaw, horizontally polarized radar signature

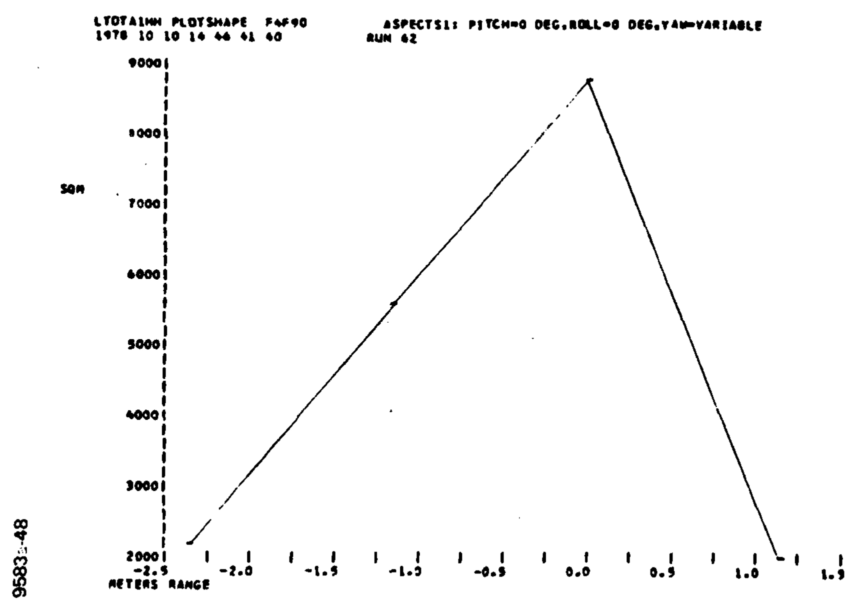


Figure E. F-4, 90° yaw, horizontally polarized radar signature

5.10 TARGET CLASSIFICATION TECHNOLOGY ASSESSMENT

The subject of target classification utilizing instantaneous wideband responses, poses many trade study possibilities.

Even if the hardware issues can be resolved, the problem of developing a target classification algorithm with a high confidence level still remains. Within the realm of microwave radar, it has been prominently noted that the use of additional discriminants such as phase and polarization enhances target recognition, and can drastically reduce the probability of misclassification.[1] Consequently, the hardware/software trade issues will deal heavily with the utilization of wideband coherent signal processing, and with target signature response as a function of the radar transmit-receive polarization status. Although Doppler-spread signatures will ultimately play a major role in two-dimensional radar imaging, it is felt that the longer required data collection time coupled with increased processor complexity will restrict its use in land based tactical radar applications for the post-1985 time frame. The system technology trade studies pertinent to target classification are outlined below:

a) The variation of signature response with aspect and polarization must be determined for a variety of targets to provide a first order estimate of dynamic range and allowable time for data collection. This study requires six man-months and 12 calendar months.

b) Development of target classification algorithm utilizing target signature responses in single target environment. Assume noise free system and knowledge of target aspect from which to infer class of target within a population of various classes. Also, utilize track data (course, speed, altitude, maneuver, etc.) as an aid in threat assessment employing simulation of realistic target scenarios. Utilize range to target and received signal level for estimate of scatterer cross-section. Determine accuracy required to bound target aspect within acceptable levels. Determine efficacy of polarization discriminant. This study requires six man-months and six calendar months.

c) Expand on (a) and (b) above in a noisy environment to determine requirements for radar power, dwell on target, and dynamic range. This study requires three man-months and three calendar months.

d) Expand on (c) for operation in chaff to determine level of spectral filtering required. This study requires three man-months and three calendar months.

e) Development of an algorithm in a multiple target scenario. Determine requirements for waveform sidelobe response and intrapulse structure. This study requires 12 man-months and six calendar months.

f) For all trade studies, determine hardware configuration and relative cost. Configure algorithm for operation in multi-sensor network for each case. This study requires six man-months and six calendar months.

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[1] TAI(1978)

In summary, the major issue which must be resolved is whether the target signature response, in conjunction with other track data, will provide sufficient discriminants to insure a high confidence level for target classification. This must be accomplished over a large population of target classes over all possible aspects, and in a timely fashion for tactical purposes. To facilitate the above, the suggested instantaneous wideband approach operating in a multi-sensor network shows sufficient promise to warrant further investigation.

Section 6

BASELINE SUBSYSTEMS AND TECHNOLOGY AREAS

6. BASELINE SUBSYSTEMS AND TECHNOLOGY AREAS

6.1 ANTENNA

6.1.1 REQUIREMENTS AND PERFORMANCE CAPABILITY

The ATR antenna must be designed to provide functional and operational survivability in the tactical environment while meeting the performance requirements for the 1990's.

The antenna design is probably the unit that is the most strongly influenced by the system requirements. Perhaps the most improtant example of this premise is the high data rate required for track-while-scan (TWS) operation. Mechanically scanning antennas are precluded by this specification, as well as by the need to avoid visual detection. An electronically agile beam directing approach in both planes is therefore required. Another important need is for low sidelobes, particularly in the azimuth plane, to counter stand-off jammers and ARM's. Wide bandwidth for LPI and target recognition narrows the choice of design approaches considerably. While not specified directly, polarization agility becomes an implied requirement because of improved performance in ECCM and target classification. The Table opposite lists the requirements imposed upon the baseline ATR antenna. It should be noted that the high performance alternate system, described in Section 8, utilizes the same antenna but with the addition of components that allow adaptive beam forming.

Table I. Requirements and Performance Capability (One Antenna Face)

Parameter	Requirement	Comment
Operating Frequency	5.3 to 5.9 GHz	Available
Instantaneous Bandwidth	400 MHz	Available
Scan Range:		
Elevation	-1° to $+60^\circ$	
Azimuth	$\pm 45^\circ$	
Top Cover Antenna	360° az 60° to 90° el	
Sidelobe level	<–50 dB intercardinal and az cardinal planes <–30 dB *el* cardinal plane	Needs improved lens design to achieve SL performance over scan range and frequency band.
Data Rate:		
Search (250 targets)	<10 sec	*Need lower losses to* achieve required effective PA product.
Track (50 targets)	< 2 sec	
Line Losses:		
Transmit	< 5 dB	Need lower loss switches, polarization network and receiver components.
Receive	< 5 dB	
Power Handling	5 kW avg	Available.
(Out of Transmitter)	50 kW peak	
Random Phase Alignment and	4° and 0.25 dB el	Need new alignment techniques, dynamic monitoring and control techniques.
Stability (relative)	2° and 0.12 dB az	
Aperture Size	12 ft wide x 13.3 ft high	Available.
Polarization		
Transmit	Any elliptical	Available.
Receiver	Diverse multiple ellipitical	

6.1.2 BASELINE ANTENNA DESCRIPTION

Four arrays are anticipated as being the optimum configuration for the baseline antenna.

The baseline approach that best meets ATR system needs is that of a four faced planar array with solid-state distributed amplifiers. The antenna parameters are given in the Table following:

Antenna Parameters

	Width		12 ft
	Height		13.3 ft
Element	Period	Vertical	1.15 in.
		Horizontal	0.84 in.
Number of Columns			171
Number of Rows			138 (276 for polarization agility)

To achieve 360° azimuth coverage it is anticipated that a four array configuration is optimum. This conclusion is based on a compromise between the total number of arrays and the azimuth scan range of each array. For wide angle scanning the loss of aperture and impedance matching becomes intolerable thereby imposing a limitation on the signal bandwidth and side lobe performance.

To obtain the necessary electrical tolerances to achieve the ultra-low sidelobe performance in azimuth, it is desirable to distribute the amplifiers in the elevation plane. (the original distribution was in the azimuth plane.) This concept was necessary since it was found to be very difficult, (perhaps impossible) to maintain the phase and amplitude variation through all solid-state modules within acceptable limits to achieve low azimuth sidelobes. In the elevation plane the sidelobe performance is less critical. Figure A shows the conceptual design with the ability for polarization agility. A conceptually simple phase and amplitude control circuit shown in the diagram permits any arbitrary polarization to be achieved on transmit. On receive the orthogonal polarization components are processed independently. The received signals from each row for each polarization are combined in two simple lenses and fed to a pair of receivers RX_1 and RX_2 as shown in Figure B. Implementation in this manner permits independent polarization processing to be carried out for maximum target enhancement.

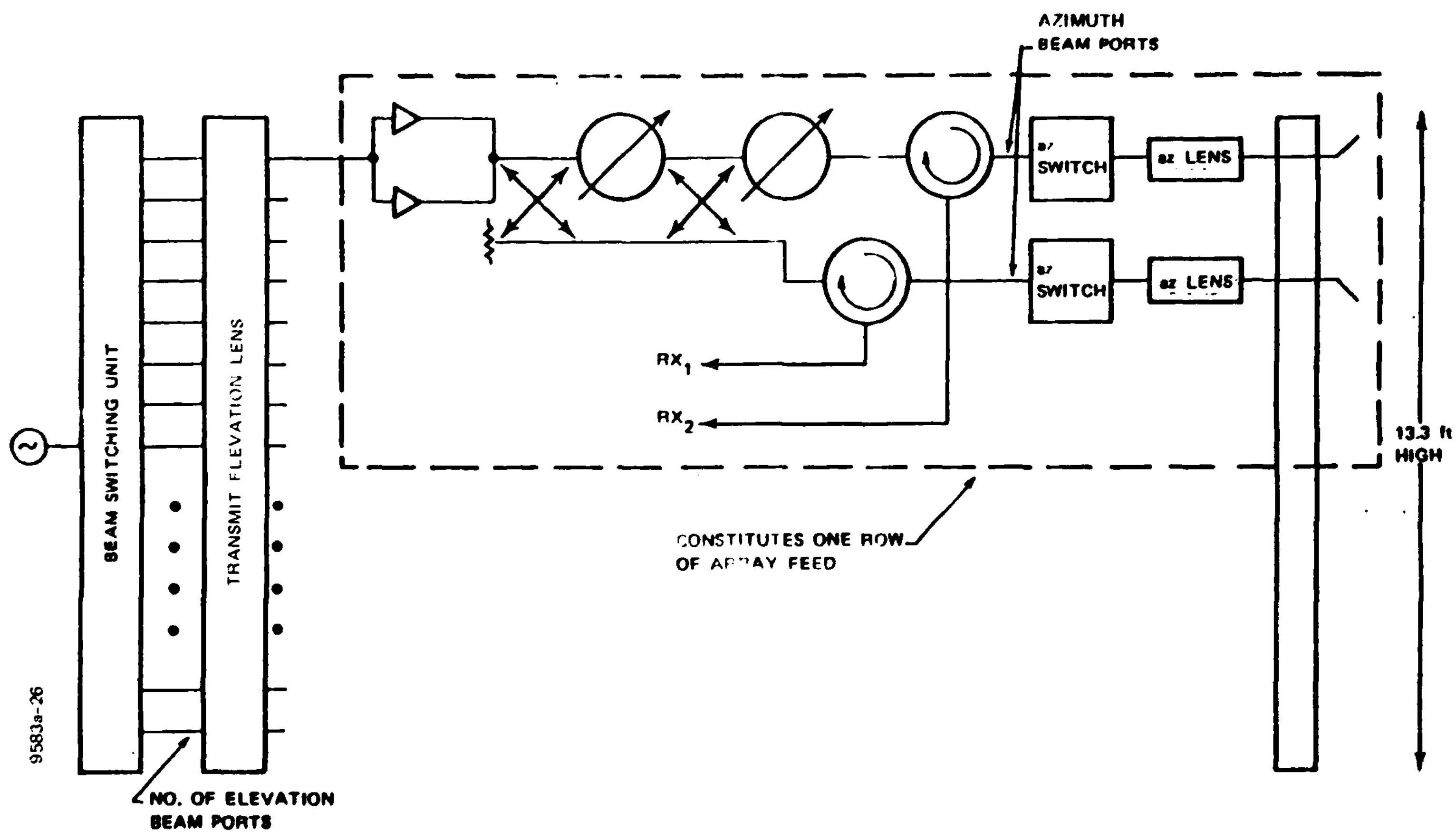


Figure A. Conceptual design of the polarization agile baseline antenna

An estimate of the losses for the baseline system is given below:

Polarization control circuit	1.6 dB
Output 10 way combiner	0.4 dB
Azimuth Switch	3.2 dB
Azimuth Lens	0.5 dB
Feed Lines to Radiators	1.0 dB
Total	6.7 dB

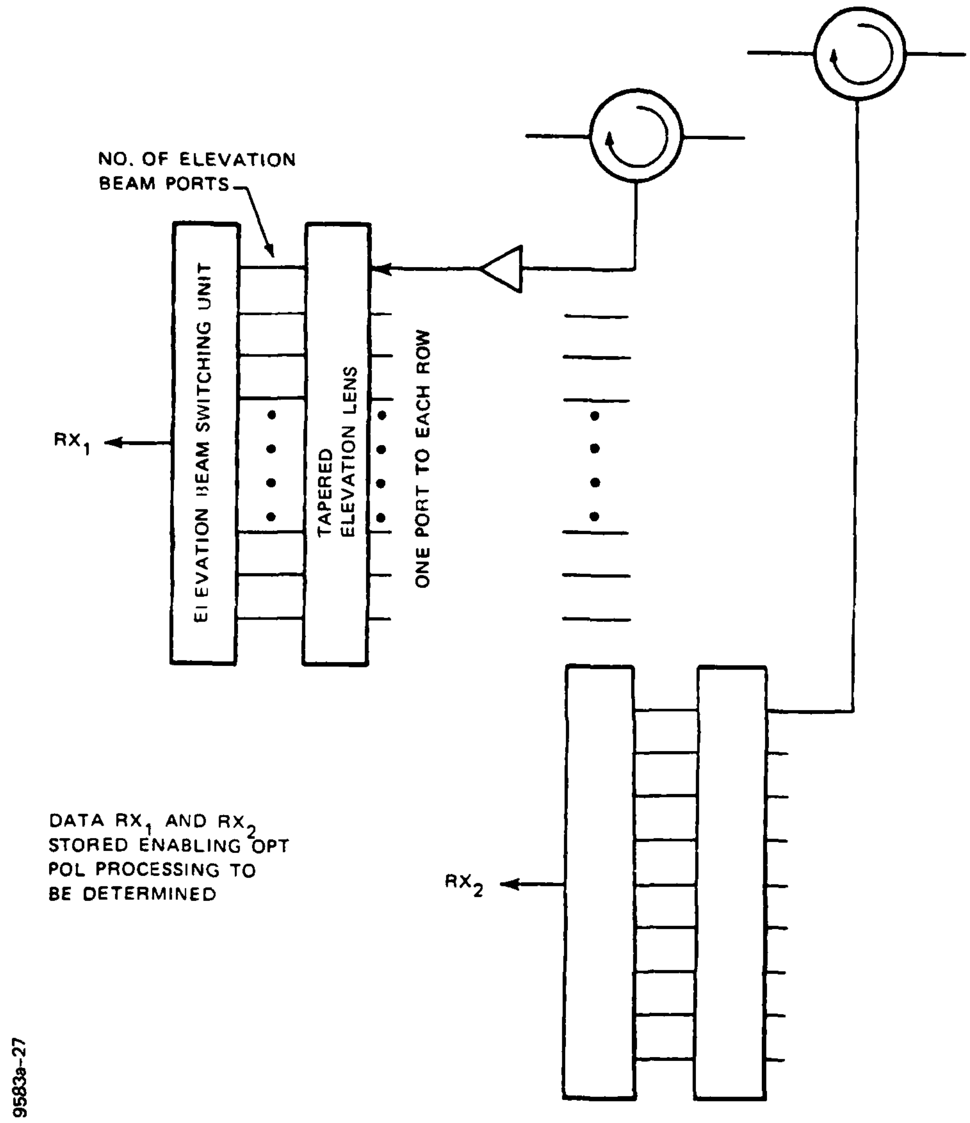


Figure B. Separate receive channels for orthogonal polarizations

6.1.3 AZIMUTH LENS DESIGN

Beam forming in the azimuth plane is done in the most cost-effective manner with Rotman lenses.

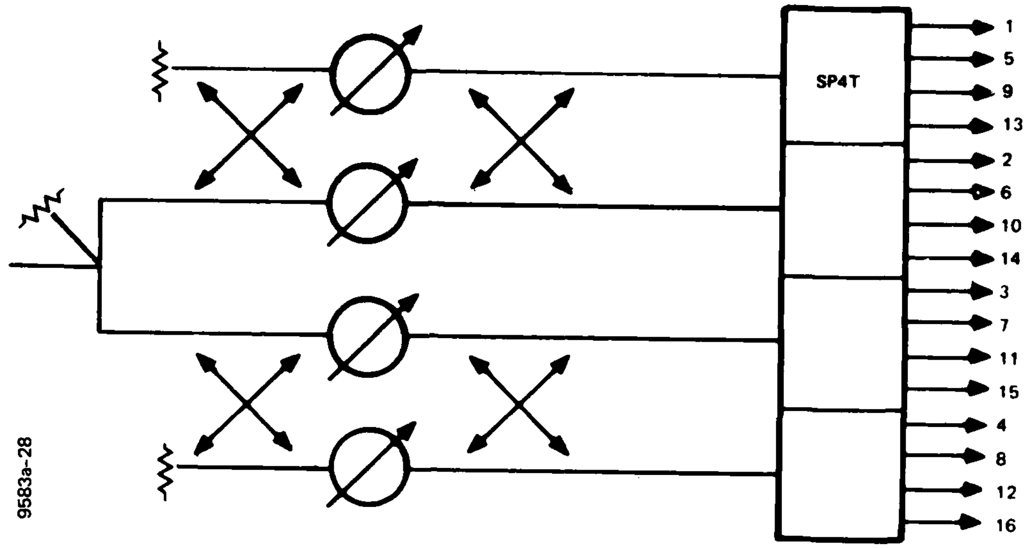
True time delay beam steering is required to meet the need for wide instantaneous bandwidth. A Rotman lens is well suited for this application. A preliminary design of a wide angle scanning Rotman lens has been obtained giving the desired low sidelobes in azimuth. The ultimate performance relies on the optimum excitation of the input subarray and the final elimination of multiple internally reflected and diffracted rays whose primary influence is to limit the achievable bandwidth. This is an area which will require further investigation to obtain a better understanding of the mechanisms involved in order to achieve a design which also permits low sidelobe performance to be achieved over the frequency band of interest.

6.1.4 AZIMUTH BEAM SWITCHING UNIT

A switching network comprising phase shifters and simple switches is envisaged which offers the flexibility of fine beam steering necessary for use in the fine track mode.

A major component of the design is the azimuth beam switching unit. Some complexity is required to achieve the sidelobe requirements since it is necessary to excite multiple input ports. A satisfactory match to the ideal focal plane fields is obtained by exciting typically a three-element subarray, although this needs to be increased to four near the extremes of the scan range.

Each row of radiators is driven by a Rotman lens where the azimuth beam direction is controlled by the azimuth switch. To achieve fine beam steering increments of 0.25 beamwidth, a variable power divider is required in the switching unit. A method of achieving this is illustrated in the Figure and is a combination of phase shifters, directional couplers and SP 4T (single pole four throw) switches. The azimuth aperture distribution desired to yield the low azimuth sidelobe performance is derived by optimum design of the lens and the appropriate excitation of the input sub-array. However, in elevation a different approach is deemed to be more convenient. In order to generate the 50 kW peak power per array, the use of distributed solid-state amplifiers is proposed. This approach affords a convenient and efficient method of deriving the elevation distribution by tapering the number of identical modules in each row feed across the array. Preliminary calculations suggest that approximately 10 identical modules, each giving approximately 50W of peak power, are driven in parallel at the center of the array while reducing the number in each row towards the edges of the array. This technique enables a course approximation to the desired distribution to be achieved which is then smoothed out by adjustment of the transistor collector voltages, giving a power variation of 1 dB maximum. In the vicinity of the edges, where only one module exists in each row, it is proposed that attenuation is inserted in the lines. Since this only applies to a moderately small number of the elements where the power is already at a low level, the associated loss of gain is predicted to approximately 0.3 dB. The azimuth aperture distribution is derived by careful design of the Rotman lens feed with the appropriate excitation of the input sub array necessary to derive the described low sidelobe pattern.



Beam weighting and switching scheme

6.1.5 FAILURE ANALYSIS

The distributed solid-state array concept in principle would appear to be an extremely satisfactory solution to meet the future requirements of the Advanced Tactical Radar.

The presence of the large number of components raises the question of reliability and the effect of certain failures on antenna performance is examined in the paragraphs following.

The beam weighting and switching scheme consists of diode phase shifters for amplitude control and SP4T switches. The digital phase shifter circuit is shown in Figure A. The failure of one diode will essentially result in the loss of that particular phase bit. This condition will lead to an excitation error of the amplitude distribution at the input sub-array to the elevation lens. It will not however, have a significant effect on the wide angle elevation side lobes since the distribution function will still be smooth, but will affect the fine stepping of the beam. The net effect on the total array will be minimal and it is anticipated that the antenna performance will not be significantly degraded. Perhaps the most significant feature will be increased VSWR in the row which will influence the signal bandwidth. It is concluded that the failure of one phase shifter can be tolerated while maintaining near full performance of this array.

The SP4T switch shown in Figure B is considered to be the most critical component. In the event of diode failure it is important that isolation properties of the switch be maintained. This isolation can be achieved at the expense of increased insertion loss in the "On" position in the event of a failure. Sidelobe performance will be maintained. The failure of a single switch near the center of the array will be most significant but even here the peak side lobes are not expected to increase above -5 dB. If isolation is not maintained between output ports of the switch, a constant relatively high side lobe will be produced in space.

Consider now the effect of failure of one solid-state module. Figure C illustrates the distribution of the modules across the array in each row. The central fourteen rows possess 10 modules in parallel. The effect of a complete module failing will cause the power to decrease by about 1 dB. The design concept allows the power to be varied by up to 1 dB and, quite clearly, the remaining modules can be driven to compensate for the power loss. Conversely, at the edges of the array the single module will give a power -10 dB below the central region but to sustain the aperture taper necessitates in excess of 20 dB of attenuation. The complete failure of a module in this region will also have an insignificant effect. The most critical region occurs in the vicinity of the 27th element where the full power is required from the module and, in the event of complete failure, a gap is produced in the excitation of the array aperture field. This field results in a sidelobe level of approximately -44 dB. Figure D shows expected sidelobe performance in elevation for the complete failure of a single module as a function of the position of the module.

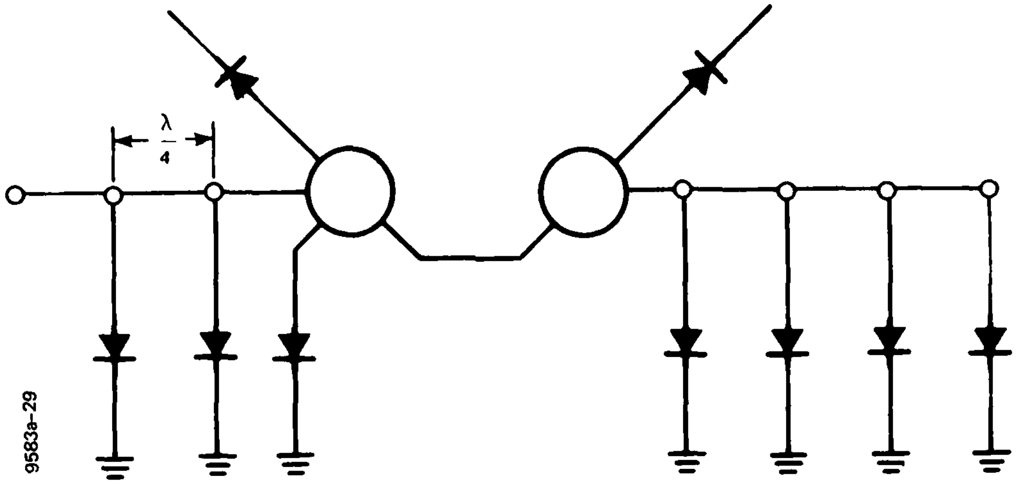


Figure A. Stripline five-bit phase shifter

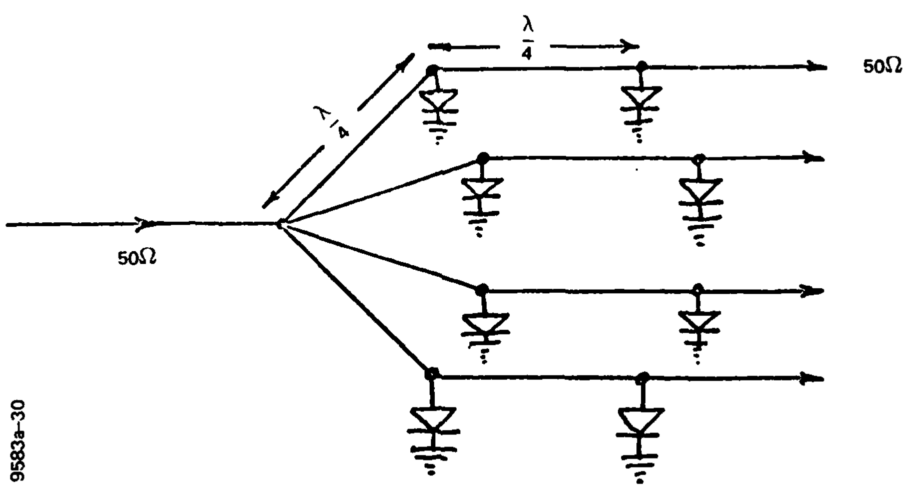


Figure B. SP4T switch

In practice it is expected that the complete failure of a single module is highly unlikely. Based on current predictions a single module will comprise about 10 transistors. The failure of N transistors will lead to a power output from the module.

$$P_o = P_{max} (10 - N/10)^2$$

Consider P modules per row where P_{max} is assumed also to be 10 then the power output per row in the event of one transistor failure is given approximately by

$$P_o = (P - 0.1/P)^2$$

In the central region P = 10 gives reduction of ~0.1 dB while near the 27th row P = 1 gives reduction of ~1 dB. Once again, taking into account the aperture taper, and the availability of voltage tuning it is calculated that 16 single transistors distributed at random through the array can fail before the wide angle sidelobes rise above the desired limit of -55 dB.

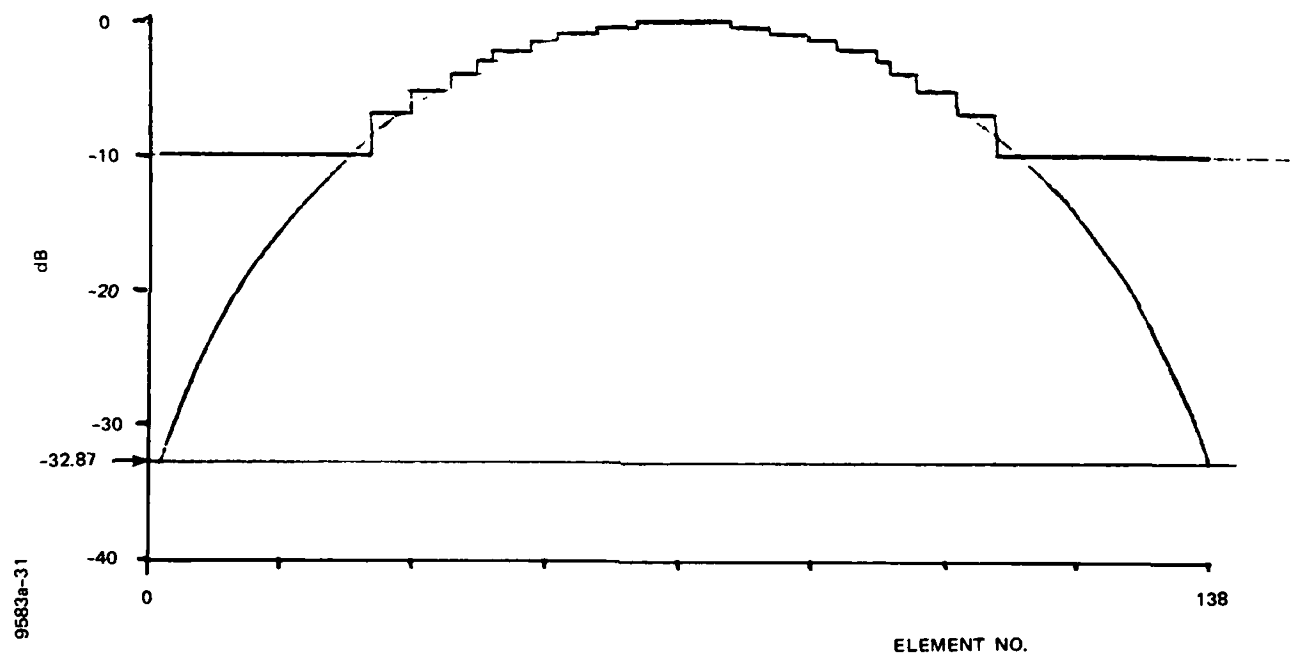


Figure C. Aperture distribution for –42 dB modified [sin(u)/u] radiation pattern

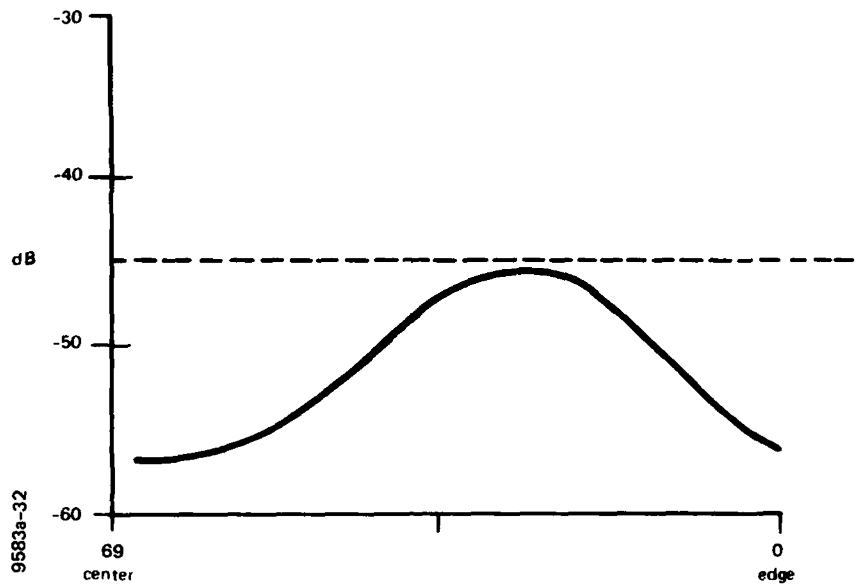


Figure D. Expected sidelobe performance (elevation) for complete failure of a single module

6.1.6 RANDOM ERROR ANALYSIS

The array design provides ideal azimuth sidelobe levels which decay rapidly to below -50 dB, and elevation sidelobe levels sufficiently below the -30 dB requirement.

Random errors in the desired beam port voltages as well as errors in the interconnecting lines are known to raise the sidelobe levels, and must be controlled to insure meeting the specifications. The elevation sidelobes are affected by random errors in the transfer characteristics of almost all of the components from the vertical Rotman lens, forward to the aperture. To meet a requirement of –30 dB, a random error sidelobe component of about -40 dB rms is required. The resulting error allowable in the aperture is equivalent to a random phase error of 4 degrees.

Note that these rms phase errors which can be achieved exhibit occasional peak errors that are much larger. Also note that most of the components are capable of being phase corrected during final assembly to achieve the budgeted error. The azimuth sidelobes are perturbed by random errors in a slightly different manner. First, only selected components contribute to the azimuth sidelobes; the horizontal beam switching network and the horizontal lens and lines. However, errors in the beam port voltages caused by the azimuth beam switching network causes changes mainly in the first few sidelobes and have a small effect on the sidelobe envelope. Since a change in sidelobe level of about 1 dB has been calculated to be caused by an error in voltage in the neighborhood of 1 dB, this error component is expected to be negligible. Thus only random errors induced by the horizontal lens and interconnecting lines need be considered in more detail.

Azimuth sidelobes are also perturbed differently than elevation sidelobes because of the column and row arrangement. Most horizontal feed random errors are expected to be different from one row to the next; similar error components are not usually caused by random tolerances and will presumably be removed by proper component design. Thus, these random errors are distributed independently over the whole two-dimensional aperture. The resulting radiation pattern from the error components is similarly distributed over all of space, rather than being concentrated in just the azimuth plane. This fact is significant relative to maintaining low azimuth plane sidelobe levels.

For example, with the design of an ideal no-error sidelobe level component of –55 dB, an allowable error component rms sidelobe level of about –63 dB is acceptable in order to meet the operational requirement of -50 dB. Due to the two-dimensional weighting, the resulting equivalent row phase error is 2.1 degrees rms. This is significantly less sensitive than the vertical error of 4 degrees rms for a –40 dB rms sidelobe level.

6.1.7 ANTENNA ALIGNMENT

The most desirable technique to ensure satisfactory alignment of the antenna is to construct the antenna with the desired electrical and mechanical tolerances thereby alleviating a costly and time-consuming evaluation program. Since the potential benefits of such an approach are enormous, it would be a worthy objective to meet this goal, and fabrication techniques and mechanical registration problems, etc., should therefore be given high priority in future studies.

It is conceivable that even in the period of the next 5 to 10 years, it will not be feasible to construct the antenna with the required electrical and mechanical tolerances to achieve the desired sidelobe performance in production. Nevertheless, means of trimming the phase and amplitude in the feed networks can be readily carried out provided these errors can be predetermined in the aperture by reliable measurements. It is assumed that the individual components, such as the Rotman lenses, feed lines to the aperture and the switching networks will be tested individually, and as integral row assemblies. The final errors, therefore, principally arise as a result of connections and mechanical tolerances where the complete antenna is put together. At this stage it is essential to measure the phase and amplitude of the aperture field to determine the location of unacceptable error sources. This method of measurement has, over the past years, and is still currently receiving much attention as an alternative technique for determining the radiation characteristics of the antenna instead of range measurements. The current state of the art, however, is such that at C-Band the sidelobe levels cannot be accurately predicted below a level of approximately −40 dB with any reasonable level of accuracy. Nevertheless, with sufficient investment it is highly probable that this technique offers the best chance of success and is considered to be the most viable means of evaluating the production antennas.

6.1.8 TECHNOLOGY AREAS

While the ATR antenna as described can probably be built with today's technology, several areas can be explored to improve performance and cut costs.

The basic principles underlying the operation of the Rotman lens are reasonably well known. Even so, to design such a configuration for operation over the desired bandwidth while maintaining ultra low sidelobes over a wide scan volume is beyond the current state of the art. The effects of internally reflected and diffracted multiple rays which arise both due to edge effects, coupling between beam ports and source characteristics needs further study to obtain a better understanding of the mechanism involved. In addition, basic differences exist between the different types of technology such as microstrip tri-plate and parallel plate waveguide, etc., which also relate to cost, performance, loss and weight, and clearly a trade-off study needs to be carried out. It is envisaged that to fully address this problem area a combined theoretical and experimental program should be initiated which is estimated to involve two man years of effort in order to reduce the risk to a low level, since there would appear to be no fundamental difficulty involved but principally a lack of available data.

Potential Methods of Loss Reduction

It is immediately apparent from the foregoing sections that to maintain the desired performance without increasing the power-aperture product of the antenna necessitates a reduction of the insertion losses throughout the system. These losses are discussed in the following paragraphs.

Dielectric Material

At present, a honeycomb-dielectric medium is proposed for all of the stripline applications in the antenna. By changing this medium to an air-dielectric stripline, the losses would improve by approximately 16 percent. However, physically implementing some of the more complex circuits now becomes a problem because of the difficulty involved in packaging air-dielectric stripline.

Low Impedance Transmission Lines

Additional improvements in insertion loss can be realized by transforming the line impedances to a lower value characteristic impedance to perform all of the RF signal processing. In doing this, one must take care not to allow the resultant line widths to approach $\lambda/4$ to avoid undesired moding.

New Switching Methods

There is a possibility that the insertion loss may be improved by utilizing a different switching scheme. This would require additional studies in new switching methods.

New PIN Diodes

Additional studies in the selection of PIN diodes may result in an improvement in insertion loss. Chip PIN diodes may also be a viable approach if methods can be developed to protect the chip in a stripline environment without introducing additional parasitics.

Dynamic Alignment

In production, the antenna will require precision assembly to maintain stringent electrical and mechanical tolerances in order to meet the desired performance in the field. Adequate BITE will immediately identify the presence of component failures and selective redundancy will be required to meet the MTBF. However, for operation in the field, it is envisaged that performance variations might occur, for example, due to environmental changes, and dynamic testing should be incorporated. A relatively simple probing technique could be used whereby output signals from each element in a row (or column) are combined to give an output which is proportional to the radiated field in a given direction. As the beam is scanned through the entire scan range in any plane, a measure of the sidelobe level would be derived. The use of a threshold detector would permit a system malfunction to be flagged in the event that the sidelobes rise to an unacceptable value. This is a critical area which clearly needs further investigation to ensure the successful operation of the radar in the field.

6.1.9 ANTENNA TECHNOLOGY RISK ASSESSMENT, SCHEDULE AND DEVELOPMENT EFFORT

An antenna configuration has been presented which meets the requirements of the new generation Tactical Radar. There are, nevertheless, critical areas in the conceptual design which need further study and development in order to demonstrate feasibility with a high degree of confidence.

The technology areas have been discussed in the previous section and an estimate of the required study and development effort is presented in the Table.

Since the feasibility breadboard demonstration would overlap the study efforts, it is estimated that a three-year total antenna development effort would be required. This effort would be directed at providing a feasibility demonstration which would essentially "prove" the critical antenna parameters and design. It is believed that the elements associated with this development program would be straight-forward and therefore low in risk.

Antenna Technology Schedule and Development Effort

Item	Calendar Time In Months	Man Month Effort
Rotman Lens Design Improvements	12	24
Antenna Line and Switch Loss Reduction Effort	12	24
Dynamic Monitoring and Alignment Technique for Low Sidelow Maintenance	18	36
Feasibility Breadboard Demonstration	18	46

6.2 TRANSMITTER

6.2.1 SOLID-STATE TRANSMITTER REQUIREMENTS AND CURRENT PERFORMANCE

The needs of the ATR for high performance RF power generation at low LCC are best met with distributed, solid-state amplifier modules.

The transmitter approach selected for the baseline design consists of a distributed (in the vertical plane) solid-state modularized concept. The module consisting of a number of RF power transistors, has a 50 watt peak power output based upon minimizing the total number of components and thus reducing cost and increasing reliability. An independent transmitter is required for each of the four planar arrays and each transmitter being distributed, is dedicated to an array face. Each transmitter is required to produce a peak power of 50 kilowatts by using the appropriate number of modules. Amplitude taper in the vertical plane is achieved by combining modules in numbers from one to ten. Taper at the edges will require the insertion of some attenuation but with negligible increase in the overall transmitter line losses. The preliminary requirements and current capabilities for the solid state transmitter are summarized in the Table.

Most of the requirements are self evident and are derivable from the system level design. The phase and amplitude stability values are based upon MTI Improvement Factors as produced by an 8 point FFT or OFT processor. The instantaneous bandwidth is derived from LPI and non-cooperative target identification requirements. The long pulse rise time provides a measure of protection against ARMs by preventing the exclusion of ground clutter multipath by an ARM leading edge gate.

The number of FET components per transmitter has been defined 6000 as a reasonable goal based upon estimated technology in the post-1985 time frame. It would appear that the smaller the number the better, as long as overall reliability is not compromised. The transmitter MTBF estimated allocation is based upon a radar MTBF of about 2000 hours.

Solid-State Distributed Transmitter Requirements
and Current Capability Summary

Parameter	Requirement	Current Capability
Operating Frequency	5.3 to 5.9 GHz	Yes
Instantaneous Bandwidth	400 MHz	Yes
Peak Power	50 kW	Yes
Average Power	5 kW	Yes
Duty Cycle	0.1	Yes
Pulse Width	50 to 270 μsec	
Efficiency (dc/RF)	$\geqslant$30%	~ 20%
Intra-Pulse Stability		Probably can meet now
Phase	5°	
Amplitude	0.5 dB	
Pulse-to-Pulse Stability		Probably can meet now
Phase	5°	
Amplitude	0.5 dB	
Pulse Rise Time	1 to 10% of pulsewidth	Yes
FETS per Transmitter	$\leqslant$6000	> 40,000
Transmitter MTBF	~ 10,000 hrs	Can probably meet with redundancy

6.2.2 SOLID-STATE TRANSMITTER DESCRIPTION

The RF power generation solid-state modules offer high reliability and ease of replacement in a small, manageable package.

A schematic of the distributed transmitter conceptual design is shown in Figure A. The elementary modules are driven from the elevation lens and fed through a switching network to the azimuth lens. The amplitude distribution of the elements, optimized for low sidelobes, is shown in Figure B. There are four configurations of power modules that can be used to satisfy low sidelobe systems. The output level of each module has a direct effect on the number of transistors to be used in the antenna system. This relationship is shown in Figure C. It is obvious that the selection of a 50 watt module is the most cost-effective approach. The amount of power required for each row of radiators can be obtained by combining a number of modules. Techniques for combining multiples from two to eight are shown in Figure D. Larger numbers of combining can be extended by using the above technique.

The primary considerations for a C-Band amplifier module are the bandwidth and power generation. The performance of bi-polar silicon devices is satisfactory at 3.5 GHz and below. The performance deteriorates rapidly above 3.5 GHz. Two terminal devices, such as Impatt and Gunn diodes can operate at C-Band but have limited efficiency.

High power GaAs FETs exhibit broad band characteristics at C-Band as typically shown in Figure E. In recent years, high power output has been realized by increasing the total gate width and the drain-to source breakdown voltage. Power output can be doubled or tripled by connecting multiple cells with internal matching techniques. Further improvement is feasible by using balanced configurations. Recent achievement of a balanced amplifier, reported in 1979, has shown power generation exceeding 10 watts above 5 GHz. Output power response versus frequency of the GaAs FET module technology is shown in Figure F.

A 50 watt module can be configured with high efficiency and reliability. High efficiency is achieved by selection of efficient transistors and by utilizing a balanced configuration and combining techniques that exhibit low loss. High reliability is accomplished by built-in redundancy and selection of low failure rate components. A typical schematic is shown in Figure G. Each transistor output stage generates in excess of 5 watts. To obtain 50 watts at the output of the combiner, only 10 of the 11 output stages are activated. Therefore, one stage is inactive and is used for standby operation. Conventional microwave power combiners do not have this fault tolerant capability (A special fault tolerant combiner is presently under development at ITT Gilfillan). Some of the attractive characteristics of solid state sources over a thermionic device, such as a TWT are: high MTBF, low noise and low phase variation due to fluctuation of bias voltage. Some FET amplifiers have been tested to show 9000 hours of operating time without failure. This life is approximately twice the operating time of a typical TWT. The power output and operating current variation as a function of time is shown in Figure H.

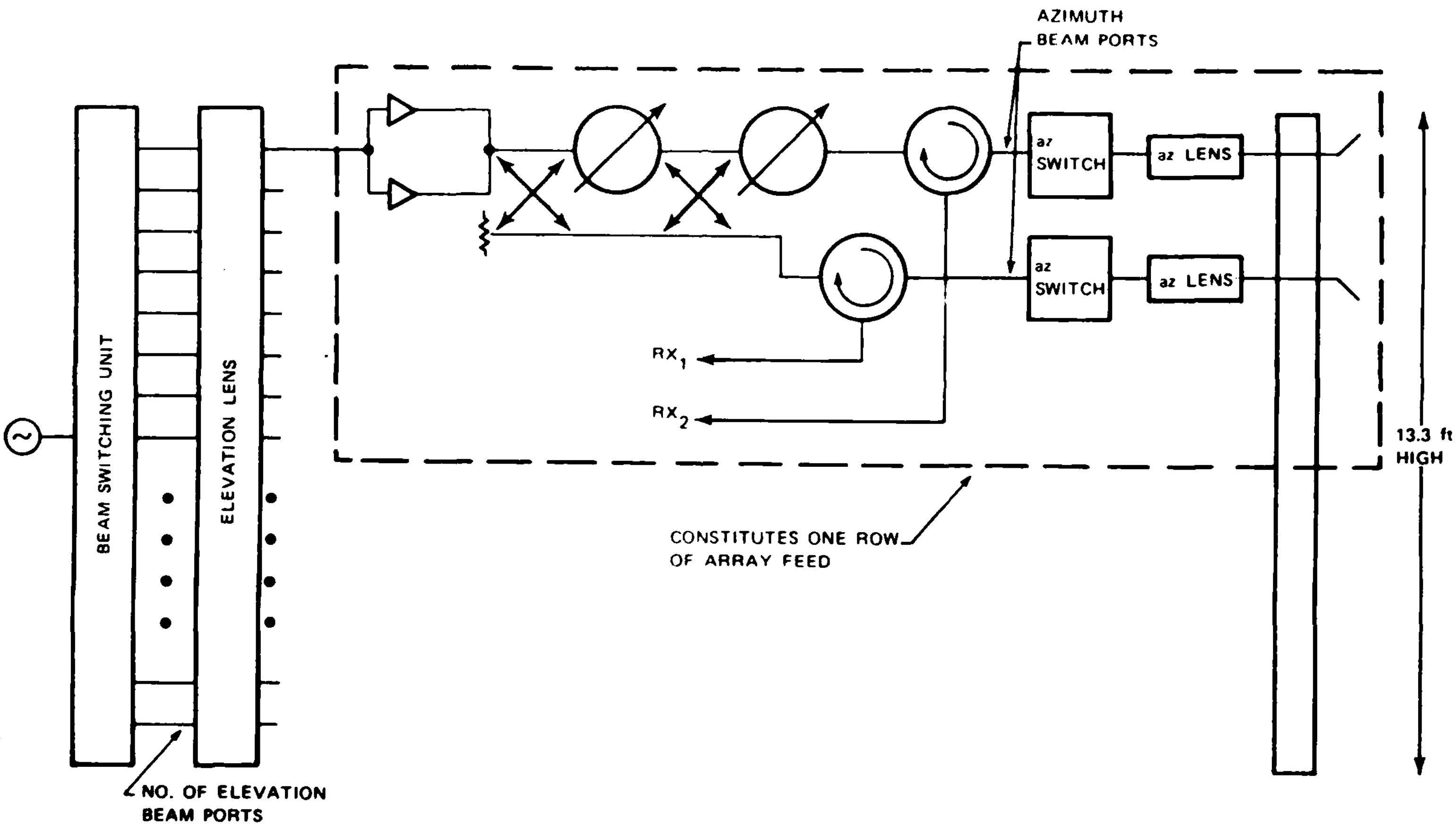


Figure A. Distributed transmitter conceptual design

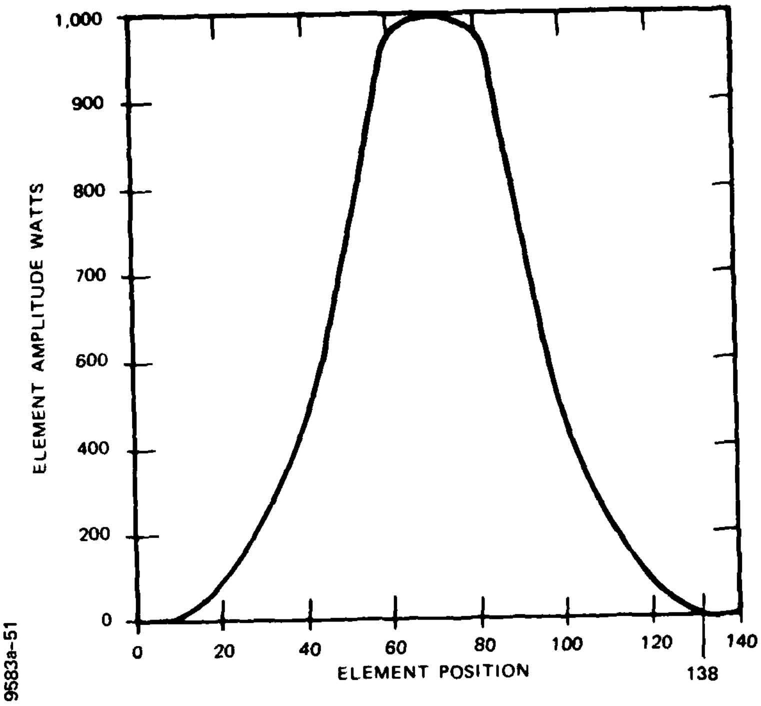


Figure B. Antenna element amplitude

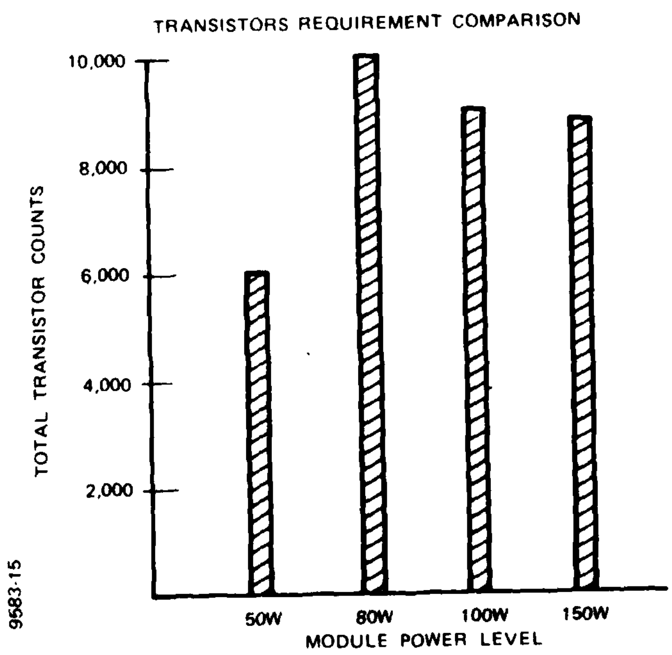


Figure C. Total transistor count variation for four different modules

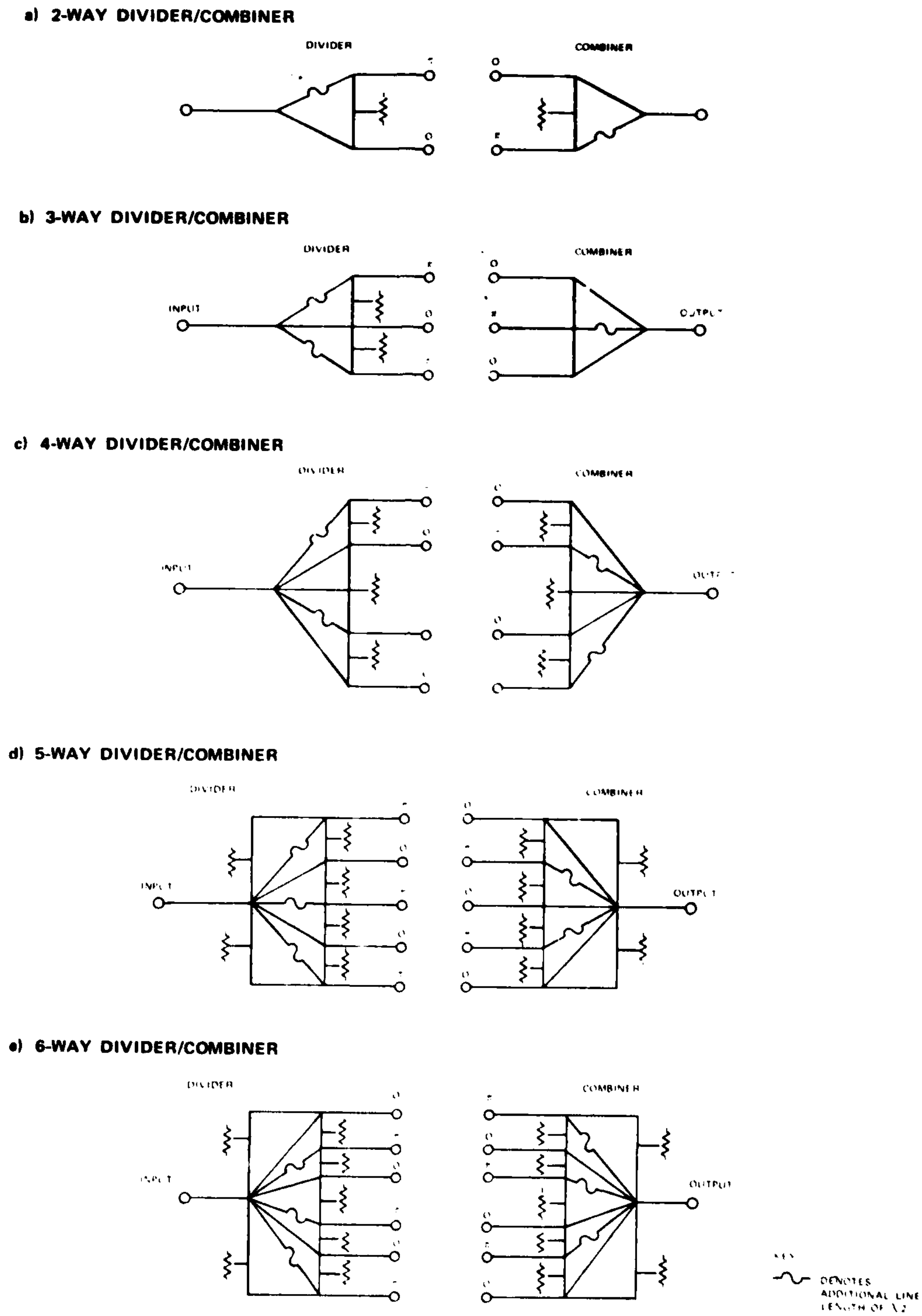


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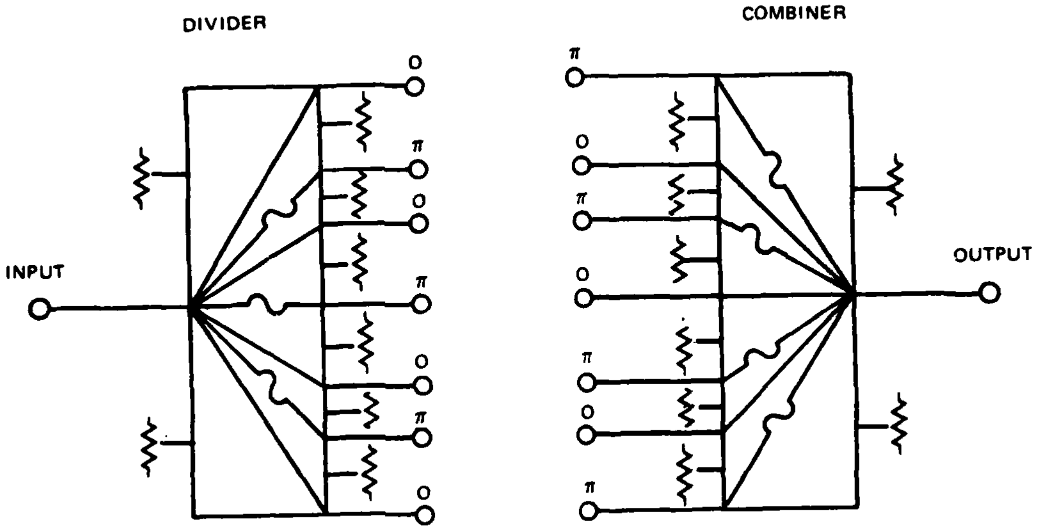
Figure D. ATR amplifier module, divider/combiner

f) 7-WAY DIVIDER/COMBINER



g) 8-WAY DIVIDER/COMBINER

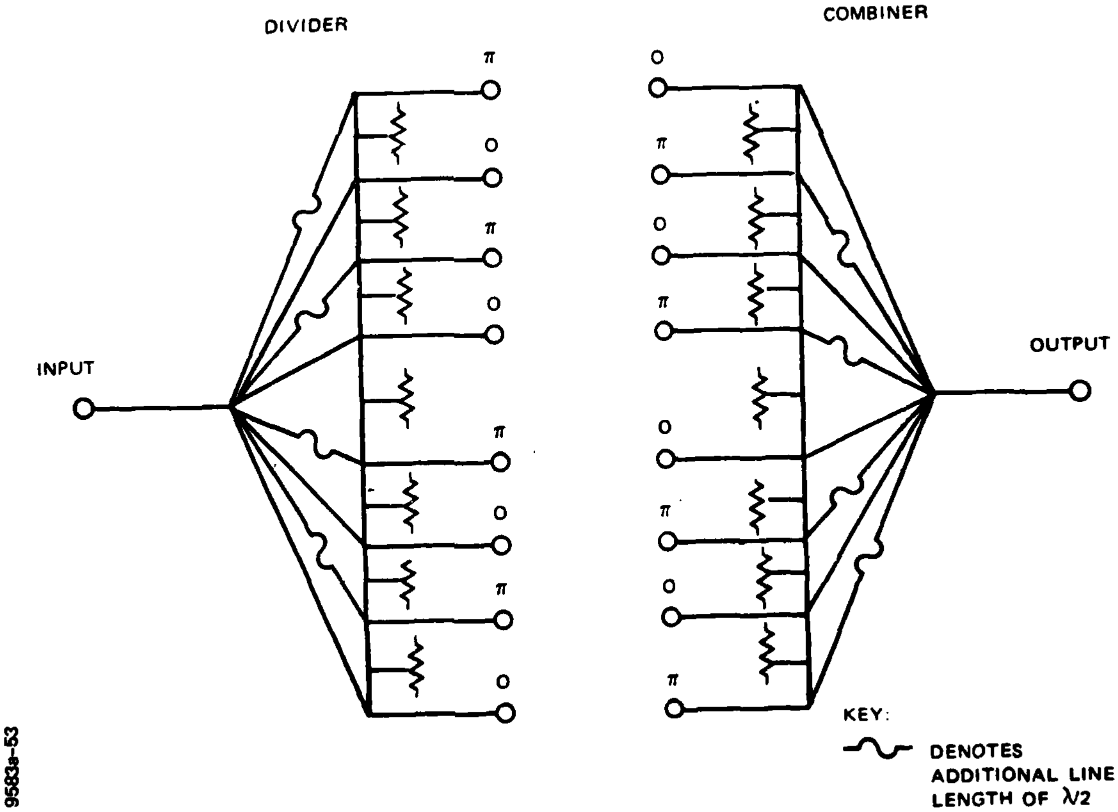


Figure D. ATR amplifier module, divider/combiner (continued)

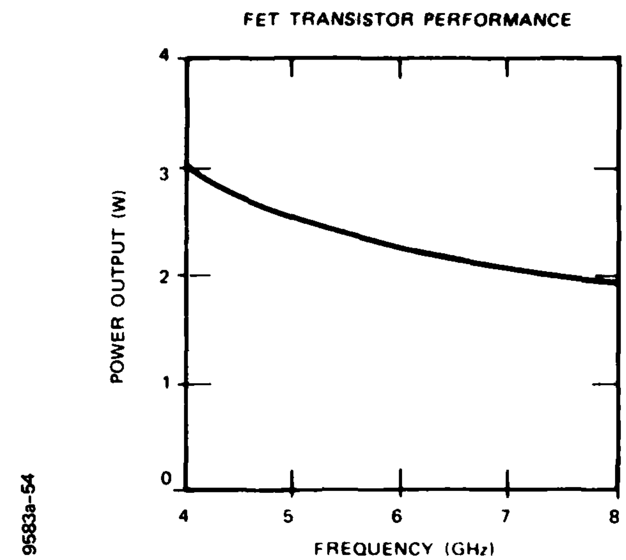


Figure E. Typical FET transistor output power

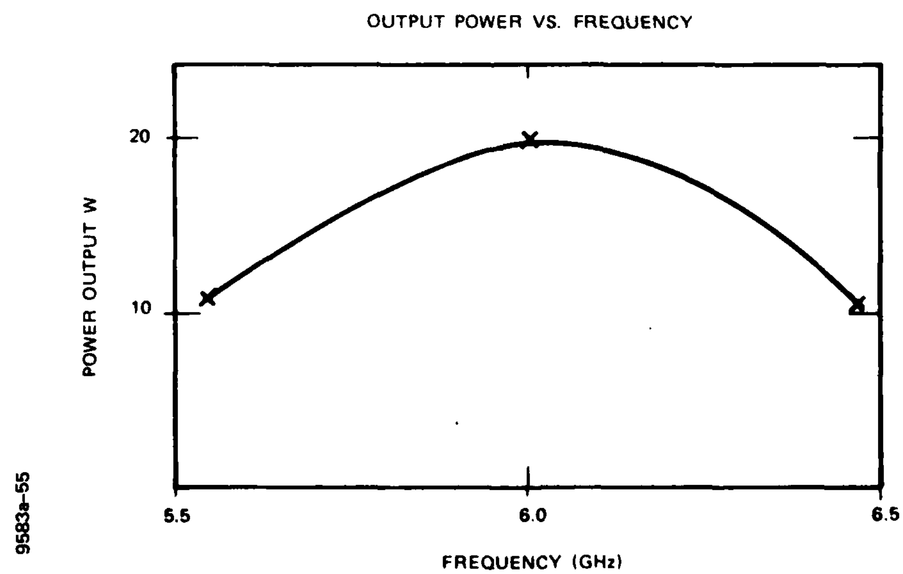


Figure F. GaAs FET amplifier module output power

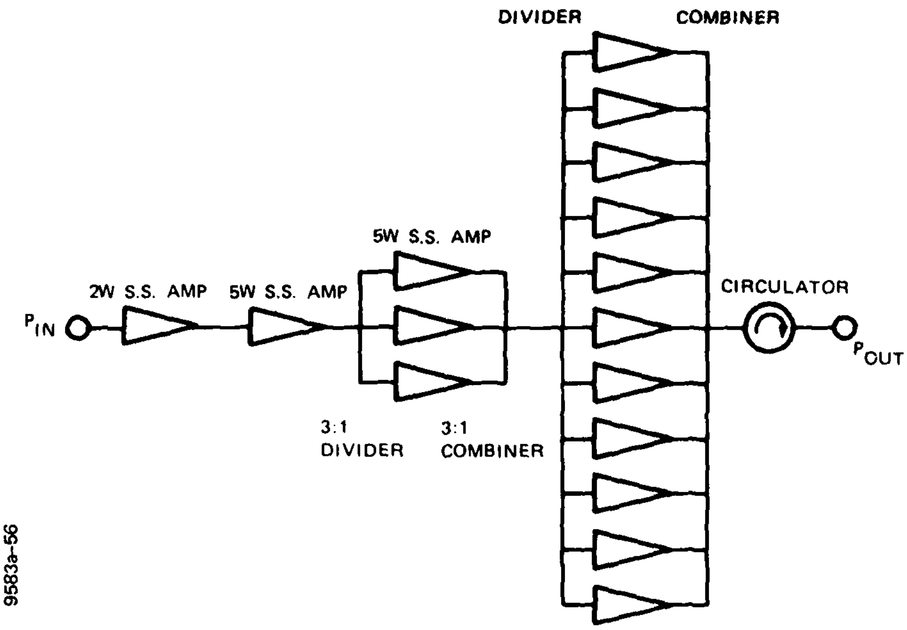


Figure G. 50-watt redundant amplifier module

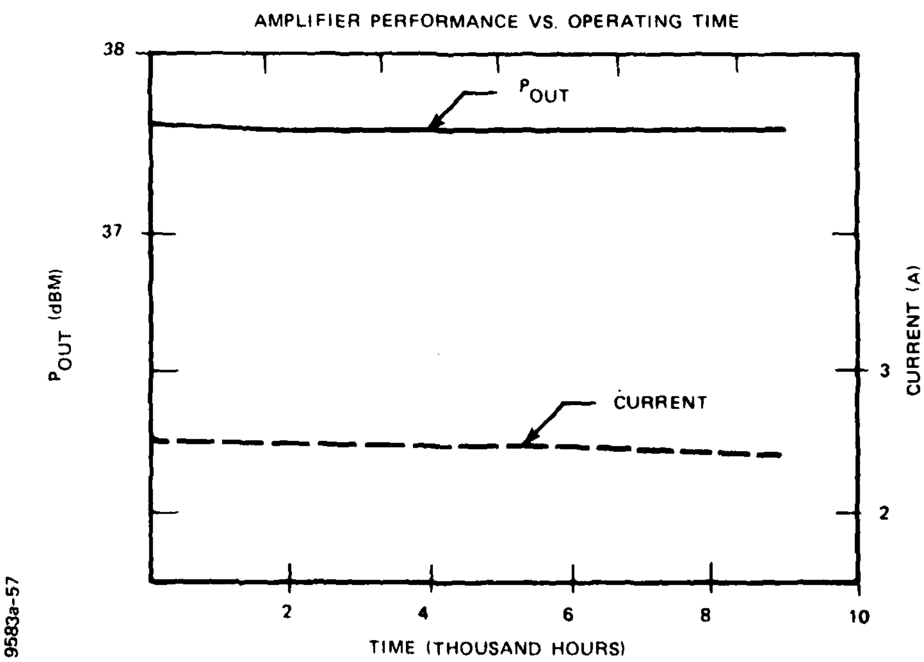


Figure H. GaAs FET amplifier performance vs. operating time

The phase noise and amplitude jitter of a given amplifier depends mostly on bias regulation. The related sensitivity is 0.2 dB variation per 0.1 volt and 2.7 degrees per 0.1 volt. Relative to the requirement of typical radar systems, bias regulations better than 0.001 volt should be more than adequate even under strenuous MTI Improvement Factor demands.

A tentative projection of 50 watt module characteristics is as follows:

Parameter	Performance
Frequency	C-Band
Peak Power	> 50 watts
Duty Factor	10%
Gain	20 dB
Efficiency	20%
Pulse Width	270 μsec max

6.2.3 SOLID-STATE TECHNOLOGY AND ESTIMATED DEVELOPMENT

While production of the solid-state module is technically feasible, a joint effort between semiconductor and radar manufacturers is required to provide modules tailored to ATR specifications

The construction of the desired 50 Watt module is not practical nor economical in 1979. But by 1985, it is entirely possible that a C-Band solid state device can generate two to three times the power output that is available now. This reality will depend on major improvements of technology in multiple cell combining, monolithic combining, upgrading drain-to source breakdown voltage, increasing the effective dissipation area, and achieving a reduction in circuit loss. Rapid maturity in L-Band device technology was significant because of a well identified market and a strong commitment by numerous solid-state device manufacturers. However, similar strong demands at C-Band have not been identified.

It would seem therefore that in the area of C-Band solid state transmitter development that a specific effort related to the Advanced Tactical Radar will be required. Using development work that has been accomplished in L-Band device technology as a guideline a rough projection of the C-Band effort can be formulated. A minimum of two semiconductor "houses" should be active in device research with each company conducting a 2 man-year engineering effort each year for a period of approximately 5 years. A parallel effort by a radar system company is required to develop module technology and low loss combining techniques. The latter effort is estimated at 4 man-years. The total effort, assuming that the required technology is peculiar to the ATR, is approximately a 24 man-year estimate extending over a calendar time of 5 years.

6.2.4 SOLID-STATE RISK ASSESSMENT

The risk in developing solid-state modules to ATR specifications thru the program previously described is manageable.

Microwave power generation, in general, using power combining technology has been practiced many years and has achieved excellent performance. However, power output in excess of 5 Watts at C-Band has not been too active. Basically there are two identified critical areas in a 50 Watt module. One is to combine 10 or more devices with very low circuit loss. This challenge is not insurmountable. The second critical area, considered more severe, is to obtain adequate and efficient output from a single device. By 1985 the probability of obtaining 50 Watts per device is 1 percent and the probability of a 10 Watt device is 90 percent. Using the above estimation, the reality of meeting the transmitter requirements can be summarized as follows:

1) The bandwidth can be met with high confidence.

2) A 50 Watt module can be built with low complexity and low risk.

3) Module efficiency can be met with a 10 watt FET device at 35 percent efficiency.

4) Duty cycle will not be a problem.

5) Pulse width and rise time will not be a problem.

6) Amplitude and phase stability is probably not a problem.

7) MTBF is reachable with redundancy.

8) To have less than 6000 devices per transmitter is estimated to have a probability of 50 percent.

6.2.5 TUBE TRANSMITTER REQUIREMENTS AND CURRENT PERFORMANCE

While many of the requirements can be met with current microwave transmitter tube technology, there are areas that require further development.

As a result of our investigation of the post-1985 requirements, the solid-state transmitter appears to be the most efficient, cost-effective approach, assuming the developments discussed in Section 6.2.1 are realized as expected. In the event that the development is delayed, or that the cost objectives are not met, a viable technical alternative exists asking an extension of existing microwave tube technology. This section describes the existing tube technology, and the required areas of development. The conclusion is that the required performance will probably be available in the post-1985 time frame as a natural result of other existing and planned programs.

The development of a tactical surveillance radar for the post-1985 time frame requires a transmitter with the performance charactersitics listed in Table I.

While many of these requirements can be met with today's transmitter technology, there are areas that require further development. These areas are related to the microwave tube selection and configuration of the radar transmitter and therefore, require careful consideration and trade-off analysis.

With today's available microwave tube technology there are no problems in meeting the transmitter requirement for RF power output, pulsewidth, gain, bandwidth and stability. The primary requirement for further transmitter developments are in reducing size and weight, increasing overall efficiency and simultaneously improving overall reliability, a formidable challenge.

The microwave tube has the greatest overall impact and its selection and utilization will determine the radar performance and its effectiveness in meeting the requirement. Microwave tubes can be utilized in a number of configurations, for example, a single chain or multiple tubes in a distributed array. Both configurations provide advantages as well as disadvantages in meeting the requirement.

Table II briefly summarizes the different types of microwave tubes that may be considered, together with ratings of applicable characteristics that will determine final selection. Idealized tube requirements for a post-1985 tactical surveillance radar may be characterized as shown in Table III, as well as the impact of sub-optimum tube characteristics. It is apparent from current manufacturer's data that no single tube type considered today meets the ideal criteria established. There is no question that, at this time, a TWT, in a single or multiple configuration, has these advantages: a) wide operating and instantaneous bandwidth with the capability of a rapid change in frequency, chirping and pulse coding, b) pulsewidth diversity, and most important, c) the flexibility to meet a changing threat environment.

Table IV is a cursory comparison of C-band microwave tubes.

Table I. Tube Transmitter Requirements/Performance Summary

Parameter	Requirement/Goal	Current	Comments
Weight	~500 lbs	2150 lbs	Unlikely
Peak Power	50 kW	50 kW	Available
Average Power (per antenna face)	~5 kW	5 kW	Available
Duty Factor	0.1	0.1	Available
Pulsewidth	~270 μsec	270 μsec	Available
Pulse Rise Time	~2.5 μsec	~2.5 μsec	Available
Short Pulse Mode	Stable output after 100 nsec	Stable output after 100 nsec	Available
Phase Amplitude Stability	0.1 dB, over one pulse 1.0 dB, pulse-to-pulse 1.0°, over one pulse 10.0°, pulse to pulse	0.1 dB, over one pulse 1.0 dB, pulse-to-pulse 1.0°, over one pulse 10.0°, pulse-to-pulse	Available
Gain	~50 dB	~50 dB	Available
Operating Frequency	5.3-5.9 GHz	5.3-5.9 GHz	Available
Instantaneous Bandwidth	400 MHz	400 MHz	Available
Efficiency	~40%	20%	Unlikely
MTBF	10,000 hours	3000 hours	Requires selective redundancy.

Table II. Microwave Tube Comparison (1979)

	Traveling Wave Tubes							
Characteristic	Helix	Ring-loop	Ring-bar	Coupled Cavity	Twystron	Klystron	Crossed-Field Oscillator	Solid State
Bandwidth	Wideband	Wideband	Wideband	Wideband	Wideband	Narrowband	Narrowband	Narrowband
Peak Power	1-10 kW	10-20 kW	20-100 kW	100-200 kW	2-5 mW	2-3 mW	0.5-1 mW	3 kW
Average Power	20-400W	400-500W	0.5-5 kW	5-10 kW	10-20 kW	5-10 kW	0.5-5 kW	150W
Voltage	9-15 kV	15-20 kV	20-40 kV	40-50 kV	130-150 kV	130-150 kV	25-50 kV	30V
Frequency Agile	Instant	Instant	Instant	Instant	Instant	Instant	Instant	Instant
Pulsewidth Diversity	Yes	Yes	Yes	Yes	Yes	yes	Yes	Yes
Efficiency	30%	30%	30%	30%	40%	45%	60%	20%
Life	*5,000 hrs*	*5,000 hrs*	*5,000 hrs*	*5,000 hrs*	*50,000 hrs*	*50,000 hrs*	*10,000 hrs*	*200K hrs*
Cost	5-10K	10-15K	15-25K	25-45K	45-75K	45-75K	35K	200K
Weight	8-12 lbs	25-50 lbs	50-100 lbs	125-175 lbs	500-700 lbs	500-700 lbs	50-75 lbs	50 lbs
Cooling	Air	Air	Liquid	Liquid	Liquid	Liquid	Liquid	Air
Availability	Available	Development	Development	Available	Available	Available	Development	Development

Table III. System Impact of Sub-Optimum Tube Characteristics

Ideal	Impact if Sub-optimum
90 dB Gain	Multiple stages required – complexity, cost, unreliability.
30% Bandwidth	Greater ECM vulnerability.
50% Efficiency	Larger size, weight, prime power, cost.
No Spurious	MIL-STD-469 compliance problems, electromagnetic incompatibility.
110 dB s/n	SCV limitation in short-pulse MTI systems, pulse Doppler.
Low Voltage	Size, weight, unreliable HV components.
No Arcing	Missing pulses, reduce availability, degraded array sidelobes and gain.
Low Cost	Increased acquisition cost of system.
50,000 Hours Life	System availability, maintainability burden, life-cycle cost.

Table IV. Comparison of Features (1979)

	CFA	Klystron	TWT	Solid-state Modules
Cost	2	3	4	5
Bandwidth (agile)	1	2	1	1
Gain	3	1	1	2
Power	2	1	2	4
Very Long Pulse	1	1	1	1+
Very Short Pulse	RF keyed: 1 Control electrode: 2 Cathode pulsed: 3	Gridded: 1 Otherwise: 4	Gridded: 1 Otherwise: 4	1
Coded Pulses	1	1	1	1
Amplitude Shaping	3	1	1	Not directly
Feedthru	1	X	X	X
Stability (MTI)	1	1	1	1
Low Noise	3	1	1	2
MIL-STD-469	2-3	1	1-2	1-2
Low Voltage	2	3	3	1
Efficiency	1	2	3	4
Life	3	2	4	1
Weight	1	2	3	4

1 – Best
5 – Worst

6.2.6 TUBE TRANSMITTER DESCRIPTION

Because of the effect of the transmitter on reliability and LCC an effort has been made to provide a design that is specifically tailored to meet the need for reliable and affordable ATR equipment.

Based on available transmitter architecture and microwave tube technology, a low-peak power, long pulsewidth transmitter has been configured to illustrate that presently available technology will not meet the post-1985 tactical surveillance radar requirements (see Table III, Section 6.2.5). A simplified block diagram of this configuration is shown in the Figure opposite.

The transmitter operates with long pulses at low-peak power with pulse compression. The 50 kW peak transmitter power at 10 percent duty cycle provides detection performance yet avoids all of the high-peak power waveguide arcing and pressurization problems.

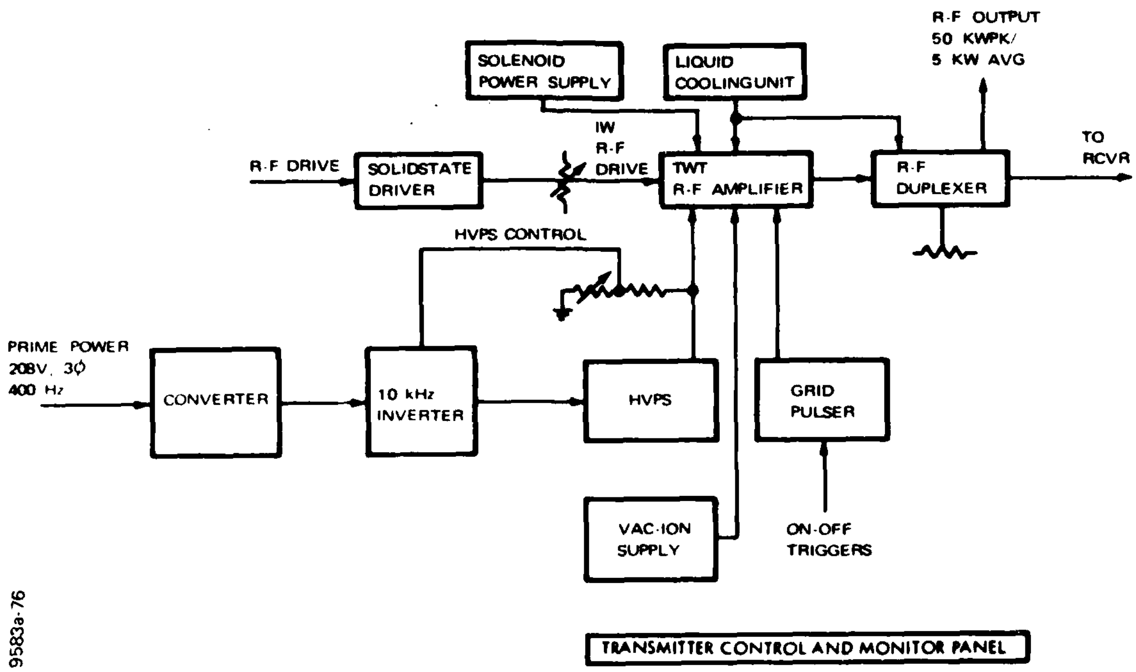
The transmitter uses a high (53 dB) gain, gridded, solenoid-focused, traveling wave tube (TWT) amplifier. High gain, low peak power and high-duty cycle capability permit the use of a single transmitter tube, thus offering maintenance simplicity and low operating costs. The TWT also permits the use of a reliable solid-state RF driver.

The transmitter features a solid-state high-voltage power supply (HVPS) which provides the cathode and collector voltages for the TWT. This supply is powered by a solid-state inverter unit which provides highly regulated 10 kHz prime power to the HVPS. The use of a high-frequency primary inverter offers several advantages. First, it provides extremely rapid and precise control response, fast enough for pulse-to-pulse regulation as is required for MTI stability. Second, it provides regulation with high efficiency at low voltages, and permits the use of reliable solid-state modular circuitry. Third, the use of high-frequency prime power inversion permits the use of lightweight transformers and simple networks for HV ripple filters.

The transmitter uses a simple solid-state grid pulse modulator which provides full pulsewidth and prf programming flexibility. This provides a low power gating pulse to the TWT grid to turn the tube on and off in coincidence with the RF drive.

A Vac-ion power supply, in conjunction with a Vac-ion pump built on the TWT, maintains a hard vacuum in the TWT and permits continuous monitoring of TWT vacuum condition giving advance indication of approaching tube wearout. A solenoid power supply is provided for TWT beam focusing. Both the Vac-ion and solenoid power supplies are interlocked with the control circuitry.

The transmitter also includes a liquid cooling unit which supplies an ethylene-glycol coolant mixture to cool the TWT, duplexer, high-voltage power supply and inverter.



A high gain, gridded TWT transmitter with solid state driver and high voltage power supply provides 5 kW average power and high stability for MTI operations

A control and monitor panel provides a centralized point for transmitter maintenance. The panel includes comprehensive features for automatic fault protection and indication, and extensive BITE features for fault localization to LRU level.

Because of the dominant effect of the transmitter on reliability and LCC, in particular the high cost transmitter tubes, every possible effort has been made to provide a design specifically tailored to the need for reliable and affordable equipment. A basic transmitter conceptual approach was selected to minimize the circuit complexity, provide all solid-state designs and reduce the transmitter to a single RF tube.

For any new radar, LCC is a major consideration. A high-gain, gridded TWT appears attractive, because it provides these essential LCC characteristics:

a) 10,000 hours operating life expectance,
b) Unlimited storage life (with scheduled preventive maintenance),
c) A 70 to 90 percent repairability and multiple repair capability,
d) A possible backup source availability.

The transmitter could be based on a modified Hughes 634H traveling wave tube (TWT) amplifier. This solenoid-focused shadow gridded C-band TWT employs a coupled cavity interaction circuit providing over 50 dB gain.

The 634H is shadow grid controlled, allowing low-power, low-voltage control of the beam current. In addition, the use of grid modulation provides complete flexibility for dynamic programming of prf and pulsewidth. The solenoid focusing is an integral part of the coupled-cavity RF circuit, minimizing the overall size and weight of the tube. The beam collector is insulated from the tube body, providing enhanced electronic efficiency of the tube by depressed collector operation.

The tube features a high perveance, Pierce type convergent flow, electron gun with excellent beam optics. Together with a ***shadow grid*** technique, these features allow grid control of high-beam power with a minimum of grid current interception, and resultant minimum grid heating. Similarly, the magnetic focusing and beam optics are designed to maximize beam transmission with a minimum of body intercept current. This is especially important at the higher average powers and long pulsewidths.

The 634H TWT high-voltage power supply (HVPS) uses a single high-voltage transformer with a solid-state bridge rectifier assembly to provide the TWT cathode and collector voltages. A capacitor filter on the cathode and collector high-voltage outputs yields clean, low-ripple voltages and provides adequate energy storage for minimum pulse droop. The HVPS is regulated by a primary inverter to achieve an overall pulse-to-pulse phase stability.

Regulation is provided by feeding back a sample of the cathode voltage from a resistive-capacitive (RC) divider to the primary inverter which operates to maintain constant cathode voltage. On the output of the HVPS, a crowbar protective circuit senses abnormal TWT current and triggers a spark gap, rapidly discharging the storage HV capacitors, and inhibiting inverter triggers. If the transmitter BITE indicates no faults, or a clearance of faults, the transmitter automatically recycles back to operate.

The 3-phase 400 Hz prime power is converted to dc power by a solid-state converter, which also includes a ramp-up circuit to reduce inrush current to the storage capacitors. The dc power is converted to 10-kHz ac power by a single solid-state inverter module.

A modular low-power solid-state grid pulser, which floats at the TWT cathode voltage, provides grid bias and turn-on pulses. Turn-on and turn-off triggers supplied by the radar programmer are optically coupled to the grid pulser. The TWT RF driving signal is bracketed by the TWT voltage pulse and thus the rf rise and fall time is determined by the RF drive signal. The grid pulse provides complete programming flexibility of pulse duration and prf.

6.2.7 TUBE TRANSMITTER TECHNOLOGY AND ESTIMATED DEVELOPMENT

Technology is currently available or being developed to meet the requirements for a post-1985 Tactical Surveillance Radar Transmitter.

While the shortcomings of presently available TWTs have been addressed, technology is presently available or being developed to incorporate improvements in performance.

The Cathode Workshop, held 30 January 1978 at NRL, Washington, D.C., highlighted the need and direction for continued development of field emitter and thermionic cathodes. Higher current densities and longer life have emerged as urgent tube requirements. Heaterless field emitters, which are unaffected by environment, will provide ***instant-on*** no-power drain capability. Both Hughes-EDD and Varian-Palo Alto, two major sources of coupled-cavity TWTs, in addition to NRL are actively working to improve cathode technology.

Recognition of the high cost of microwave tubes has resulted in a trend towards the use of laser cutting, electron discharge machining, and computer-controlled milling in tube development leading the way to lower production cost.

Adaptation of multielement depressed collectors, and samarium-cobalt magnets have resulted in improved tube prformance, and a trend towards a re-examination of the materials and the fabrication technology for innovative application to new designs has emerged.[1] Examples of continuing microwave tube and technology developments can be found in the AGED Project Briefs.[2]

The microwave tube is a major radar architectural element and its choice determines the requirements for power conditioning and the mechanical configuration and packaging of the transmitter.

In the last few years there has been a great emphasis on power conditioning. The use of high-frequency converter/inverters has improved transmitter power conversion efficiency as well as reduced size and weight. ITT Gilfillan has been active in developing advanced power conditioning, incorporating a high-frequency converter/inverter in a production radar transmitter and presently furthering this development on IR&D. High-frequency power conditioning has also lead to the reduction in size and weight of magnetic components. ITT Gilfillan has an IR&D program aimed at lightweight, high-voltage magnetics.

[1] AGED. Annual Report, Calendar Year 1978 (Washington, D.C.: Office of the Under Secretary of Defense, Research and Engineering, 1978)

[2] AGED, Project Briefs, Annual Report 1978 (Washington, D.C.: Office of the Under Secretary of Defense, Research and Enginering, 1978).

6.2.8 TUBE TRANSMITTER RISK ASSESSMENT

Present trends in microwave tube developments and radar transmitters architecture will not change post-1985 radar transmitters significantly. Technological refinements will result in improved performance and a reduction in development risk.

Based on present trends in microwave tube development programs and available information on radar transmitter developments, it is not anticipated that there will be any significant changes in post-1985 radar transmitter architecture. Emphasis will be in making basic improvements in performance and trying to achieve the ideal transmitter. Improvements in component materials and processing will result in improved reliability, not only in microwave tubes but also in high-voltage magnetics. Improvement in efficiency will also result in reduced power dissipation and improved life and reliability with a reduction in life-cycle cost.

6.3 RECEIVER/SYNTHESIZER

6.3.1 REQUIREMENTS AND CURRENT TECHNOLOGY

The baseline system concept leads to a relatively simple receiver. The bandwidth, noise figure, dynamic range, etc., are all available or achievable now, and require no new technology development.

The requirements and current technology status of the receiver is shown in Table I.

The required performance parameters are:

- Frequency is dictated by system design approach.
- Bandwidth is constrained by waveform design.
- RF STC (Sensitivity Time Control) and protection is required to protect the low noise preamplifier from saturation or burnout. The 40 dB STC was derived based upon a maximum/minimum range ratio of 200/20 corresponding to 40 dB of STC.
- RF protection is based upon assuming an open circuit on one of the high power distributed transmitter lines resulting in a large amount of reflected power into the receiver.
- Gain of 30 dB is assumed to achieve excellent isolation of following high loss circuits and thus a minimal noise figure.
- RF Amplifier noise figure is dictated by system sensitivity requirements.
- Dynamic range of 60 dB is based upon a range variation of 40 dB and a target variation of 20 dB.

Table I. Preliminary Receiver Requirements/Capability Summary

Parameter	Requirement/Goal	Comment
Operational Frequency	5300 to 5900	Available
Instantaneous Bandwidth	400 MHz	GHz or greater available
RF STC	40 dB	60 dB or greater is available
RF Protection	550W to 2.8 kW peak nominal	Readily available
	28W to 55 kW peak fault	
	Average power 6 to 280W	
Gain	30 dB	Readily available
RF Amplifier Noise Figure	2.0 dB	Achievable with present state-of-the-art
Dynamic Range	$\geqslant$60 dB	Achievable with present devices

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6.3.2 RECEIVER DESCRIPTION

The receiver is a simple homodyne configuration to achieve maximum capability for large instantaneous bandwidths with RF STC (Sensitivity Time Control) and utilizing doubly balanced mixers for the quadrature I&Q phase detectors in both the horizontal and vertical channels.

The baseline receiver approach utilizes a centralized single channel receiver for the horizontal and vertical components. The baseline configuration is shown in block diagram form in Figure A.

In the baseline configuration, the receiver protector would be a passive Transmit/Receive Limiter (TRL), rather than a diode limiter. The TRL can accommodate significantly higher incident power levels. In this configuration the losses in the receiver protector can be reduced to the 1 to 1.3 dB region while providing excellent receiver protection even during fault conditions. The radioactive gas pre-TR cells have a limited life of 5,000 to 10,000 hours, but can easily be replaced at a replacement cost of approximately $250.

In the area of the receiver protector and RF STC present solid-state devices could adequately protect the receiver for the nominal or normal expected peak or average power.

The selection of GaAs FET devices for RF amplifiers provides excellent phase linearity, and gain flatness characteristics over 10 percent of greater bandwidths. Typical curves of gain and phase deviation from linear versus frequency is shown in Figure B. At present, GaAs FET devices are available with noise figures in the 1 to 1.5 dB range at 5 GHz with projected goals of 0.6 to 0.8 dB within a year. The curves in Figure C are of currently available GaAs FET bipolar, low-noise devices.

New Technologies and Estimated Development Schedule

No new technologies would be required to meet the baseline receiver requirements. It is anticipated that the needs of on-going satellite communications programs will provide continuing improvements in both the noise figure of the GaAs FET devices and the availability of the medium power linear devices.

Risk Assessment

Essentially no risk is estimated in achieving the requirements of the baseline approach.

Alternate Low-Loss Configuration

In the baseline receiver configuration (Figure A), it was illustrated that the system receiver losses include losses due to the Elevation Beam Focusing Rotman Lens and the Elevation Beam Switch Networks. It is possible, though not currently practical, to reduce the effect of these losses by at least 1 dB at the system level by placing the limiter and RF amplifier on the input side of the Rotman Lens. This configuration requires 138 limiters and RF amplifiers (see Figure D).

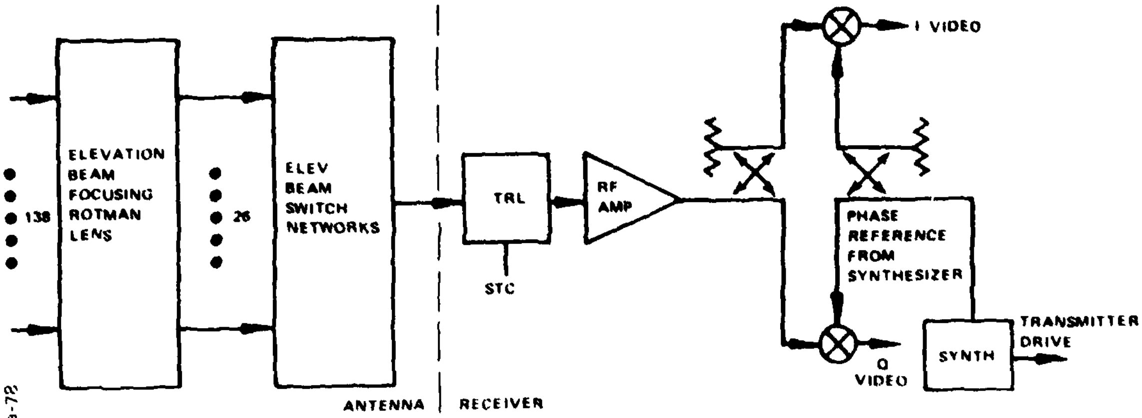

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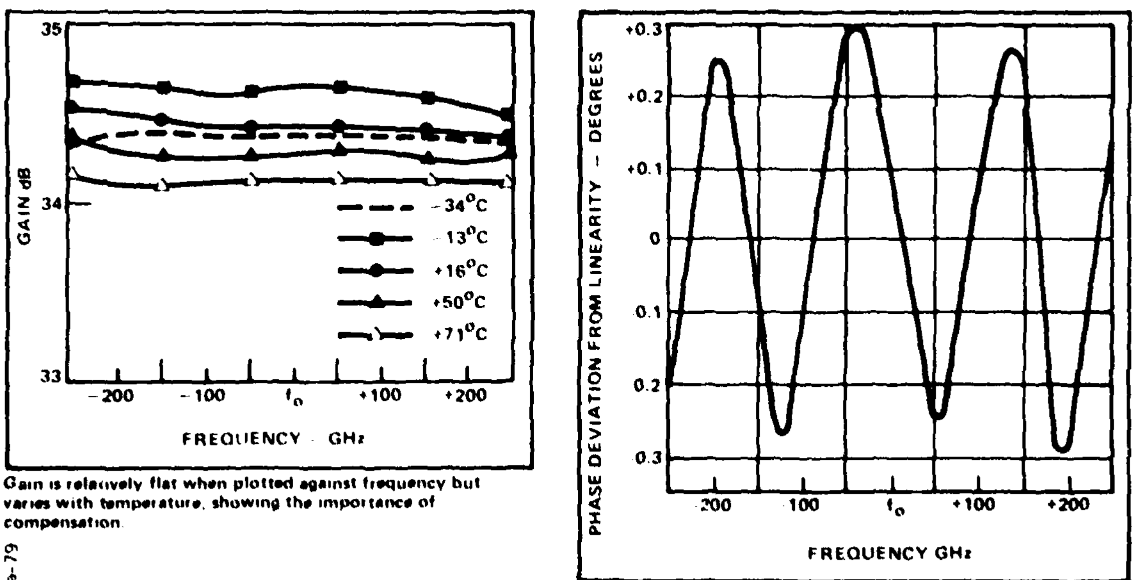
Figure A. Baseline receiver configuration.



Gain is relatively flat when plotted against frequency but varies with temperature, showing the importance of compensation.

Phase deviation from linearity is plotted against frequency for a satellite amplifier's driver.

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Figure B. Typical amplitude and pulse characteristics of GaAs FET amplifier.

In addition to the obvious cost and complexity penalties, this approach would require matching of gain and phase (to within 1/2 dB and ±2 degrees), between 138 limiters and RF amplifiers, including the effects of STC. This approach is moderate to high risk at this time, but could be considered if normal technology development produced the requisite low-cost components (such as multi-amplifier chips).

Current on-going IR&D in the areas of digitally-controlled, fast-switching synthesizers will meet all the requirements of the ATR. Recent IR&D developments in the medium power linear amplifiers used in the coherent transmitter drive chain exhibit substantial improvements in the instantaneous bandwidths, pulse-to-pulse amplitude, and phase stability and intrapulse characteristics which will meet the requirements imposed by the advanced waveform technology.

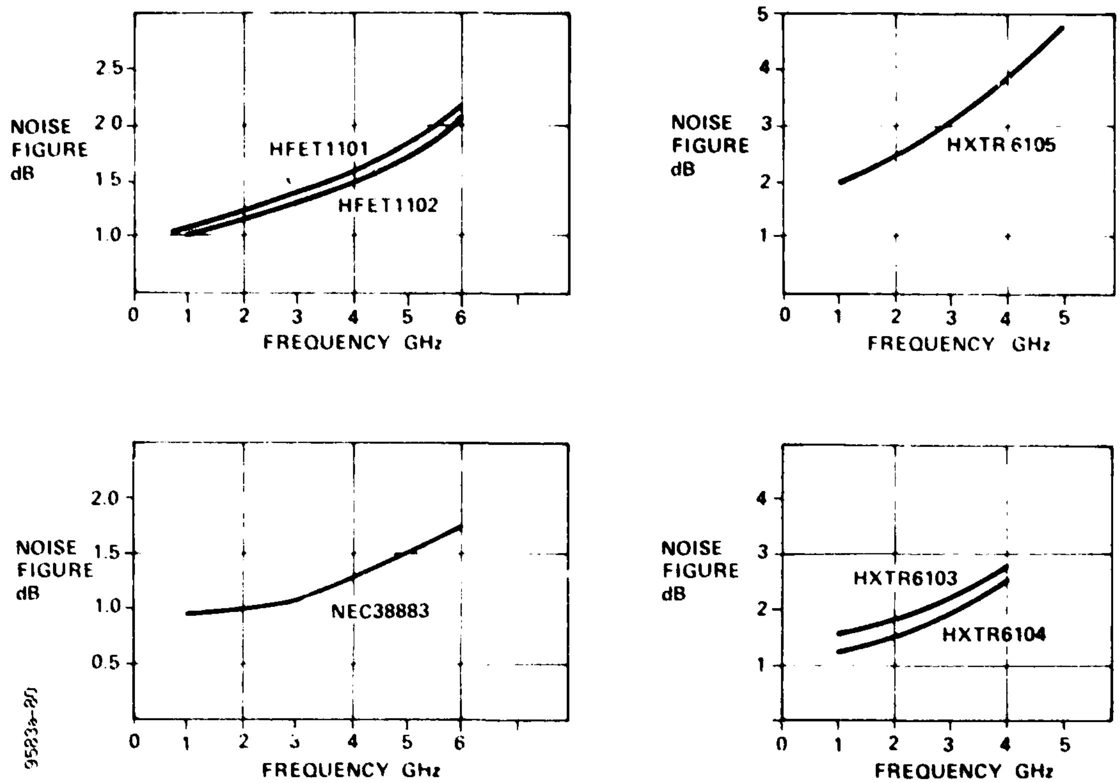

Figure C. Noise measurements for current off-the-shelf GaAs FET bipolar devices.

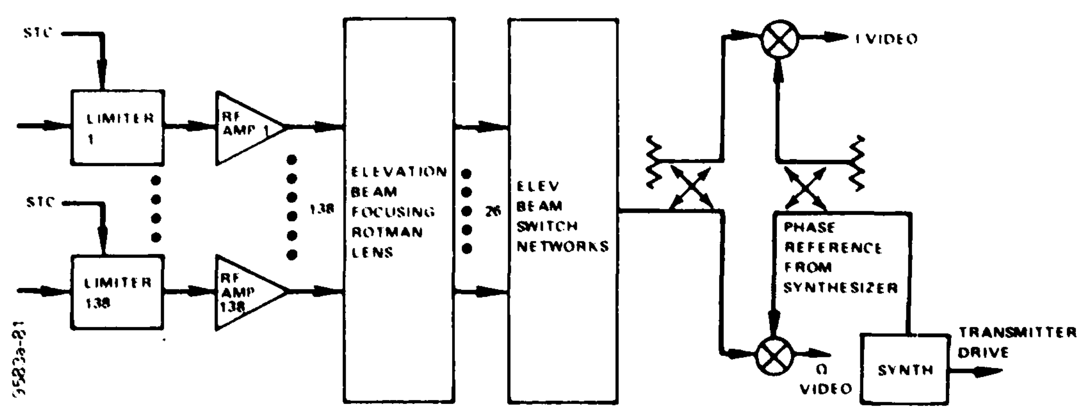

Figure D. Alternate low loss receiver configuration.

6.4 PROCESSOR SUBSYSTEMS

6.4.1 SUMMARY OF THE PROCESSOR SUBSYSTEM REQUIREMENTS

Performance requirements are summarized for signal processing, data processing, and wideband signal processing functions in the processor subsystem.

A processor subsystem suitable for use with the post-1985 Advanced Tactical Radar (ATR) was configured for the purpose of evaluating both the adequacy of existing technology and the necessity of developing new technology for use in the ATR. A summary of the major performance characteristics of that processor subsystem is given in the Table following.

The design methodology which was used to develop the baseline processor and its associated performance characteristics is given in Section 6.4.2, along with a discussion of the processor subsystem block diagram. The signal processor configuration of the baseline processor subsystem is discussed in further detail in Section 6.4.3. Size and power estimates for the baseline processor subsystem are provided in Section 6.4.4. Finally, technology development requirements for the baseline processor subsystem are discussed in Section 6.4.5.

Performance and technology development requirements for the wideband signal processing mode are described separately in Section 6.4.6. Estimates for this mode were not included in the power and volume estimates made for the baseline processor since its performance requirements far exceed the capabilities of the existing technology.

A risk assessment for meeting required technology development objectives in the 1985 time frame is provided in Section 6.4.7.

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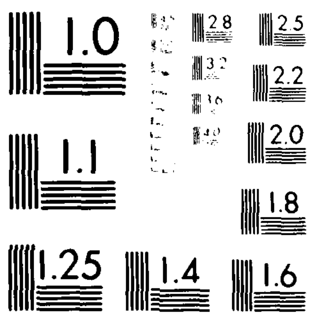


MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

Summary of the Major Characteristics of the Processor Subsystem

SIGNAL PROCESSOR FUNCTIONAL REQUIREMENTS

Analog/Digital Conversion

Polarization Channels: H&V (Dual Channel Processor)

Quadrature Phase: I&Q

Environment:	Clear/Terrain/Rain	Chaff
Sample Rate	13 MHz	26 MHz

Dynamic Range: 11-bit

Doppler Spectral Filtering

Environment:	Clear/Terrain	Rain	Chaff
Spectral Filter used:			
Single Channel Processor	Simple Canceller	8-point DFT	NOF (6 Filter Bank)
Dual Channel Processor	Polarization Matrix	Polarization Matrix	Polarization Matrix

CFAR

Hard limited bi-phase pulse compression

Pulse Compression

Environment	Clear/Terrain/Rain	Chaff
Waveform:		
Pulsewidth	250 μsec	62.5 μsec
Bandwidth	6.5 MHz	13 MHz
Code Length	1626 segments	813 segments
No. of Doppler Channels	21	7
Detection:	Envelope, $(I^2 \& Q^2)^{1/2}$ Greatest of Double Samples Greatest of Doppler Channels Greatest or Spectral Filters	

DATA PROCESSOR AND SYSTEM CONTROL FUNCTIONAL REQUIREMENTS

Processing/Control Functions

Processing Functions	Control Functions
Sky Clutter Mapping	Scan Programming
Terrain Clutter Mapping	System Synchronization
Correlation Detection	Automatic Processor Test
Automatic Clutter Residue Mapping	Automatic Processor Reconfiguration
Target Parameter Extraction	
Target Tracking	
Message Formatting and Reporting	

Summary of the Major Characteristics of the Processor Subsystem (Continued)

WIDEBAND SIGNAL PROCESSING FUNCTIONAL REQUIREMENTS

Analog/Digital Conversion

Quadrature Phase: I&Q
Sample Rate: 400 MHz
Dynamic Range: 6-Bit (Chaff)
1-Bit (Clear)

High-Speed Memory

Memory Word Size: 12-Bit (6-Bit I, 6-Bit Q)
Memory Write Cycle: 400 MHz (Effective)
Memory Length: 1.1 X Pulsewidth = 110K-Words

Processing

Spectral Filtering
Pulse Compression

BASELINE PROCESSOR

Physical Constraints

Volume: 30 cu ft
Prime Power: 7.5 kw

6.4.2 DESIGN METHODOLOGY

The design of the baseline processor subsystem is described in terms of its functional block diagram.

Functional requirements for the baseline processor subsystem were initially developed from the results of the ATR system requirements analysis and the ATR baseline system synthesis which were conducted as a part of this study and which are described elsewhere in this report. These functional requirements were translated into a processor system structure by mapping each functional requirement into a functional processing unit within that processor.

Three major categories of functional requirements were identified:

- signal processing requirements
- data processing requirements
- system control requirements

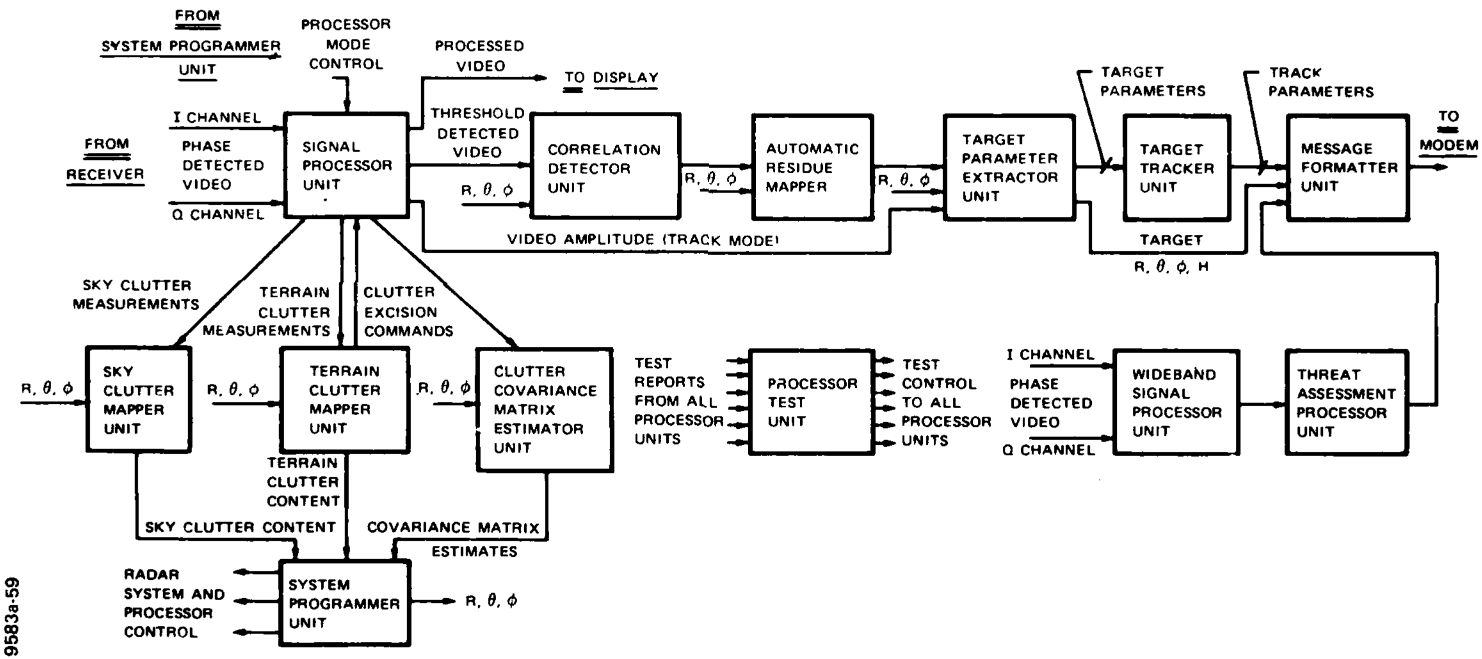
Based on recent design experience of 3D radars at ITT Gilfillan, the data processing and system control functional requirements were mapped onto functional units which are configured using programmable, general purpose micro-computers along with random access memory (RAM), control store, read only memory and input-output interfaces. These micro-computer based functional units were then sized by comparing requirements for the ATR radar with requirements for existing or proposed radars for which design base data was available. Sizing in each case was limited to providing a unit of average capability to meet the defined requirement in the ATR. Further study is required at both the system and subsystem level to provide refined estimates of required capabilities in these areas.

Signal processing requirements were estimated assuming high speed, special purpose processor units. Estimates for the signal processor were based on preliminary designs since it was assumed in advance that the signal processor requirement would represent significantly greater processing throughout than previous signal processors, and that the existing technology would be most stressed in the signal processing requirement area.

<u>**Processor Subsystem Block Diagram**</u>

A simplified block diagram of the processor subsystem is given in Figure A. The baseline processor consists of thirteen functional units.

The baseline processor contains a Signal Processor Unit and nine functional units. The Signal Processor unit receives quadrature channel phase detected video from the receiver and provides threshold detected video to the Correlation Detector unit. The Signal Processor Unit also provides processed video to a display unit. A Sky Clutter Mapper Unit and a Terrain Clutter Mapper Unit form three dimensional maps of the measured sky and terrain



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ATR (single quadrant) processor block diagram

environment. The outputs of these maps are used by the System Programmer Unit to adaptively control waveform and scan program mode selection as a function of the changing environment. The output from the Terrain Clutter Mapper Unit is also used to excise returns from the zero Doppler filter in radar cells which have been mapped as containing terrain clutter.

Threshold detected video from the Signal Processor Unit is noncoherently integrated by the Correlation Detector Unit. This unit deletes threshold crossings due to thermal noise which are spatially uncorrelated and reports only potential targets to the Automatic Residue Mapper Unit. The Residue Mapper unit maps clutter residue not removed by the Signal Processor Unit. Declared targets are reported to the Target Parameter Extractor Unit by the Residue Mapper Unit, and reports resulting from clutter residue are suppressed by this unit. Target parameters are extracted by the Target Parameter Extractor Unit, and are reported to both the Target Tracker Unit and to the Message Formatter Unit which transmits the radar output messages to the command and control system. The Target Tracker Unit reports track parameters to the Message Formatter Unit. A Processor Test Unit controls automatic testing within the processor subsystem and evaluates test results from the units under test. Redundant units are automatically switched on line in response to detected faults by the Processor Test Unit.

6.4.3 SIGNAL PROCESSOR CONFIGURATION

Three signal processor configurations were evaluated for use in the baseline processor.

A simplified block diagram of the Signal Processor unit is given in Figure A. The Signal Processor Unit provides for

- analog-to-digital conversion
- Doppler spectral filtering
- hard limited CFAR
- binary phase coded pulse compression

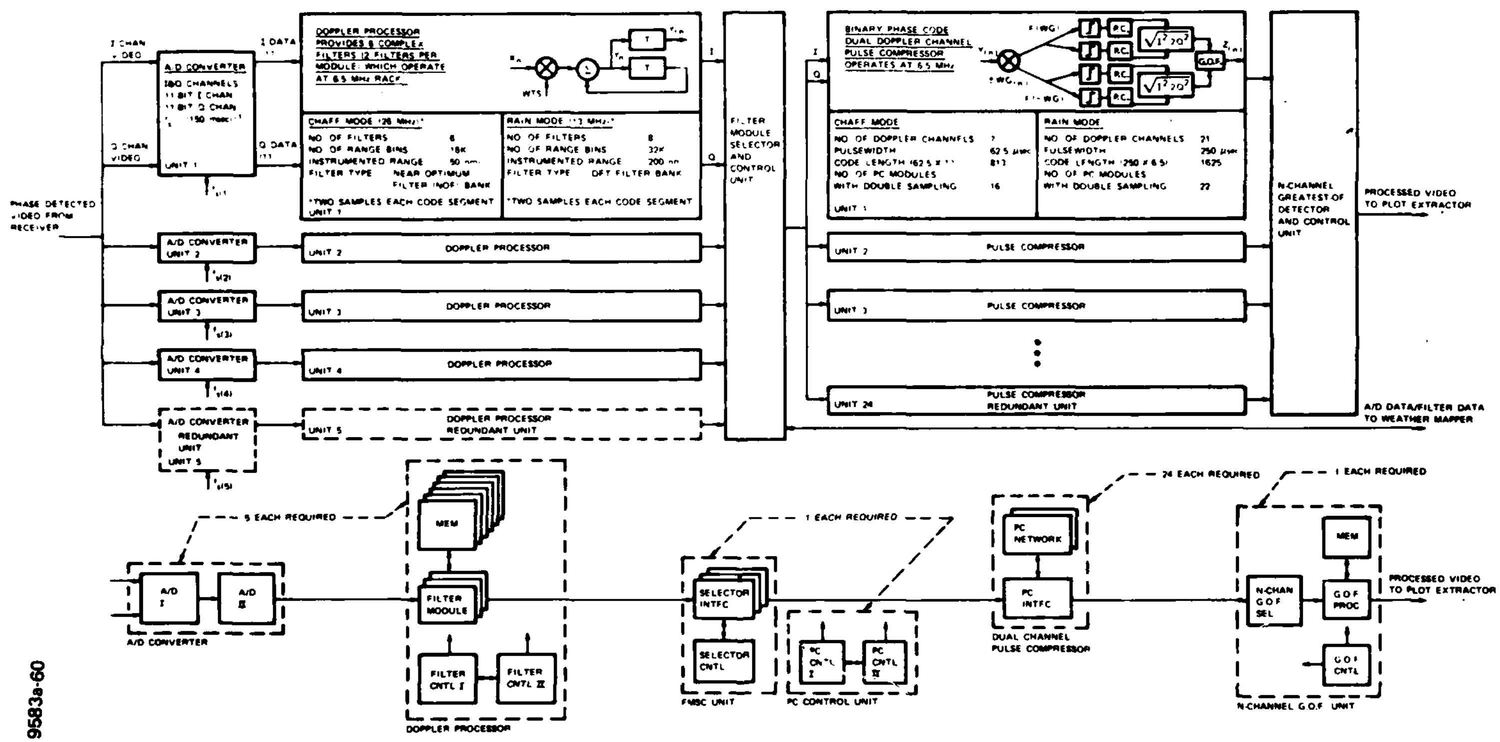
The baseline Signal Processor has a Doppler spectral filtering requirement for a single channel of processing with three modes of operation: clear, rain and chaff.

Clear mode provides a conventional canceller with an unambiguous instrumented range of 200 miles. Rain mode provides an eight-point DFT filter bank with 200 miles of unambiguous range. Chaff mode provides a Near Optimum Filter bank with 50 miles of unambiguous range. Range sampling is done at 13 MHz for clear and rain modes and at 26 MHz for chaff mode. (Double sampling or two samples per code segment are taken.)

In addition to the single channel baseline, estimates were made for two dual channel (horizontal and vertical polarization) configurations. Dual channel configurations use a polarization matrix processing algorithm for spectral processing.

A single common filtering element consisting of a complex multiplier, a complex accumulator and a 200 mile data memory element was used in the preliminary design since this single structure is capable of supporting all of the required spectral processing modes. As shown in the diagram, six filter elements are provided per Doppler processor with four Doppler processors provided per signal processor. The fifth Doppler processor and A/D converter are spare redundant units. This configuration provides a total of 24-filter elements which operate at a 6.5 MHz sample rate. The chaff mode requires 24, the rain mode requires 16, and the clear mode requires 2. The pulse compressor was configured using a dual Doppler channel pulse compressor module. The 250 microsecond rain mode pulse requires 21 Doppler channels of pulse compression; the 62.5 microsecond chaff mode pulse requires 7 Doppler channels of pulse compression. For purposes of this study, the 813-bit and 1625-bit code lengths were estimated assuming a 768-bit and 1536-bit code, respectively. Doppler compensation was provided using a single complex multiplier for each complex conjugate pair of channels. Hard limited CFAR is applied after Doppler compensation and before compression. Two spare redundant pulse compression channels are provided.

The outputs of the 21 active pulse compression channels are combined in an N-channel detector. The greatest output of this N-channel detector for each of the filters in the filter bank is selected for a given range bin. This value is thresholded and sent to the Correlation Detector Unit in the plot extractor.



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Signal processor unit block diagram

6.4.4 PROCESSOR SUBSYSTEM SIZE AND POWER ESTIMATES

Size and power estimates are provided for the baseline Processor Subsystem.

Size and power estimates for the baseline Processor subsystem are provided in Table I for each of the three Signal Processor configurations studied. Board count estimates were initially developed for the single channel base line. These estimates were then scaled to meet the requirements of the dual channel matrix and the dual channel matrix (2 MHz) configurations. Volume estimates were developed by estimating 0.4 ft^3 per logic board. Power estimates were developed by allowing 75 watts per logic board.

Size and power estimates are in excess of those required in a tactical radar environment. Significant reductions in both size and power are necessary. These reductions can be brought about in several ways.

Component technology development over the next five years (1980 - 1985) will obviously contribute to a significant size reduction (throughout the Processor) and in some areas (random access memory, for example) to a significant reduction in power consumption. Alternative Signal Processor architectures should produce some improvement by providing a better match between processing elements and the several adaptive processing modes which are required within the baseline system design.

Table I. Size and Power Estimates for the Baseline Processor Subsystem Using 1979 Technology

		Single Channel Baseline	Dual Channel Matrix	Dual Channel Matrix (2 MHz)
SIGNAL PROCESSOR	L/C Boards	147	305	72
	Volume (ft^3)	58.8	122.0	28.8
	Power (kW)	11.0	22.9	5.4
DATA PROCESSOR	L/C Boards	33	37	37
	Volume (ft^3)	13.2	14.8	14.8
	Power (kW)	2.5	2.8	2.8
PROCESSOR SUBSYSTEM TOTAL	L/C Boards	180	342	109
	Volume (ft^3)	72.0	136.8	43.6
	Power (kW)	13.5	25.7	8.2

6.4.5 TECHNOLOGY DEVELOPMENT REQUIREMENTS FOR THE PROCESSOR SUBSYSTEM

Technology development programs within the areas of digital correlation, random access memory, random logic, and sequential control logic, can provide up to a 50 percent reduction in power and volume from the 1979 technology baseline.

An analysis of the dual channel processor provided a list of eight categories of processing circuits which are used throughout the processor. Estimates of the percentage of a logic board which each category represented were developed for each logic board type in the subsystem. These percentages were then summed across all of the logic boards in the base line processor to provide an estimate of the percentage represented by each of the eight categories. The results of this analysis are shown in the Figure.

As shown in the Figure, 34.9 percent of the baseline processor is dedicated to digital correlation (this stems from the large time bandwidth products associated with the binary phase coded waveforms and the related intrapulse Doppler shift of high velocity targets). In fact, over 80 percent of the dual channel processor subsystem is concentrated in only four processing circuit categories. These are:

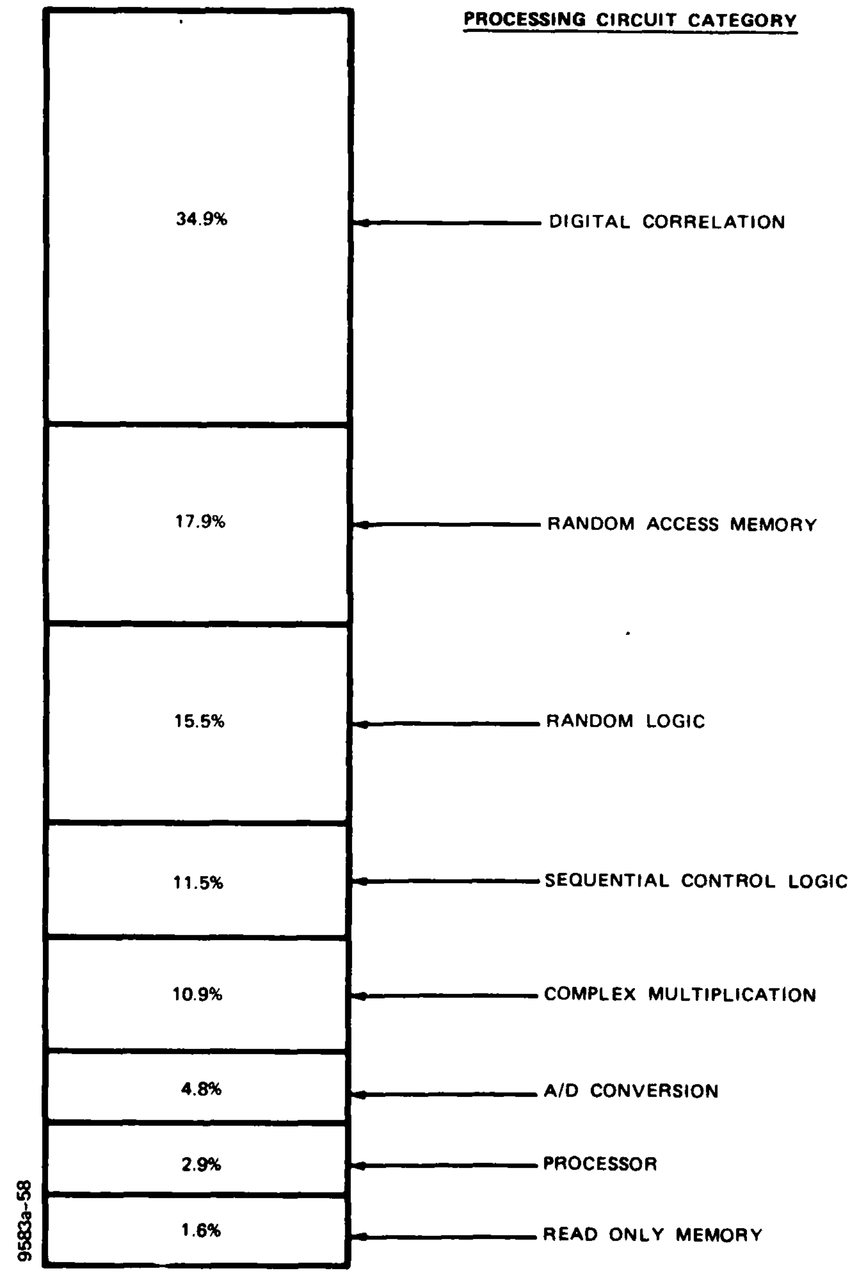
- Digital Correlation
- Random Access Memory
- Random Logic
- Sequential Control Logic

The remaining 20 percent of the processor subsystem is composed of four additional processing circuit categories.

- Complex Multiplication
- A/D Conversion
- Micro-Processors
- Read Only Memory

Criteria for Selection of Technology Development Candidates

Analysis of the data presented in the Figure leads to the conclusion that different approaches to technology development are required for the eight categories. For example, though the two categories of random logic (15.5%) and sequential control logic (11.5%) represent 27 percent of the baseline processor, no single integrated circuit can be used (without modification) throughout the processor to meet the varied requirements that these two categories represent. However, for the two categories of digital correlation (34.4%) and random access memory (17.9%) which represent 52.8 percent of the baseline processor, it is possible that a single digital correlator circuit and a single random access memory circuit could be developed, and that these two circuits could be used throughout the processor to substantially reduce processor size and processor power consumption.



Dual channel processor subsystem (1979 technology base) expressed in terms of eight processing circuit categories

Selection of technology development candidates should be based on the following considerations:

- Percentage of usage for the candidate in the 1979 baseline processor.
- Degree of integration for that candidate available in 1979.
- Expectation of further technology development for that candidate through 1985.
- Cost of achieving a desired degree of integration for that candidate in 1985.
- Risk of achieving a desired degree of integration for that candidate in 1985.

Additional Factors Effecting Technology Development

Several of the integrated circuit technology categories required for the ATR baseline processor (e.g., random access memory, complex multiplication, micro-processor and read only memory) will benefit from predictable evolutionary trends within the integrated circuit industry over the next 6 year period. Historically, these evolutionary trends improve performance as the technology matures and thereby provide for an overall reduction in both size and power for the mature technology.

In addition to the evolutionary performance improvement trends cited above, the very high speed integrated circuit (VHSIC) technology development program currently being funded by the Department of Defense has targeted selected signal processing building blocks such as complex arithmetic processors, high speed A/D converters, dual port random access memories and programmable controllers for development. It is likely that useful signal processing building blocks developed under the VHSIC technology development program could also be useful in the design of the ATR processor.

Required Technology Developments

The design goal for a post 1985 baseline processor is 3 cubic feet for volume and 7.5 kW for power. These goals represent volume and power reductions of 78 percent and 71 percent respectively from the 1979 baseline. An average reduction of 50 percent represents a more realistic goal for the eight categories presented in the Figure over the 1979-1986 time frame. In order to achieve this reduction, three key elements should be available. These are:

1) A 512-bit digital correlator chip capable of operating at 6.5 MHz with a power dissipation of 6 mW per bit. (The 1979 baseline used a 64-bit correlator with a power dissipation of 12 mW per bit – TRW TDC1023J).

2) A 16K-bit random access memory chip capable of performing one read cycle or one write cycle every 75 nanoseconds with a power dissipation of 0.05 mW per bit. (The 1979 baseline used a 4K-bit chip with a power dissipation of 0.10 mW per bit).

3) A set of LSI uncommitted logic arrays capable of supporting a 6.5 MHz data rate and sufficiently flexible for efficiently implementing the majority of the random logic and the sequential control logic categories of the 1979 baseline processor. (The 1979 baseline used MSI/SSI components with an average power dissipation of 250 mW per package.)

6.4.6 WIDEBAND SIGNAL PROCESSOR UNIT

Meeting the requirements for wideband signal processing depends on technology developments in A/D converters, high speed shift register memories, and gigabit layer switching speeds.

The Wideband Signal Processor Unit (Figure A) is used to develope a target signature report on a selected target with a known range, Doppler and local clutter environment for use in threat classification. A very high-speed (200 MHz data rate) A/D converter and buffer memory unit samples the received waveform at the range of interest for a duration slightly greater than the transmitted pulsewidth, and transfers this data (at a reduced data rate) to a random access memory. When required, additional samples are acquired in the same manner. Then, these samples are Doppler filtered and pulse compressed. The target signature report is extracted from the output of the pulse compressor and sent to the Threat Classification Processor Unit.

Timing Constraints

In order to develop an estimate of the processor hardware requirements, various assumptions were made regarding the collection of wideband data operating at a nominal radar prf of 400 Hz.

Target signatures are input during the 0.5 sec of special mode time allocated for each 10 sec scan period. (See Figure B.) This time is nominally divided into 20 subperiods of 25 msec each. A 2.5 msec prf would then allow for collecting up to 10 pulses on a target per subperiod. This establishes a requirement of 2.5 msec to transfer the contents of the High-Speed Buffer Memory to the Random Access Memory and of 0.475 sec to develop a target signature report once the data has been collected.

Memory Organization

An all digital High-Speed Buffer Memory organization could be based on the use of a high-speed shift register memory such as that shown in Figure C. The size of the shift register memory is directly related to the time bandwidth product of the waveform as shown in Figure D. A trade-off exists between the size of the High-Speed Buffer Memory, and the maximum rate we are willing to transfer data into the Random Access Memory. In the limit, the distinction between the memory types disappears and sufficient High-Speed Memory is provided to store up to 10 samples from the target with no Random Access Memory provided. Because of the required size of the memory however, it is likely that minimizing the size of the High-Speed Memory would also minimize the cost of the total memory.

A/D Converter Requirements

As shown in Figure A, both in-phase and quadrature channels are converted by the A/D converter. The minimum conversion rate for a 200 MHz binary phase modulated waveform will be 400 MHz per channel. This provides two samples per code segment per channel. A minimum of six-bits dynamic range for the converter is required.

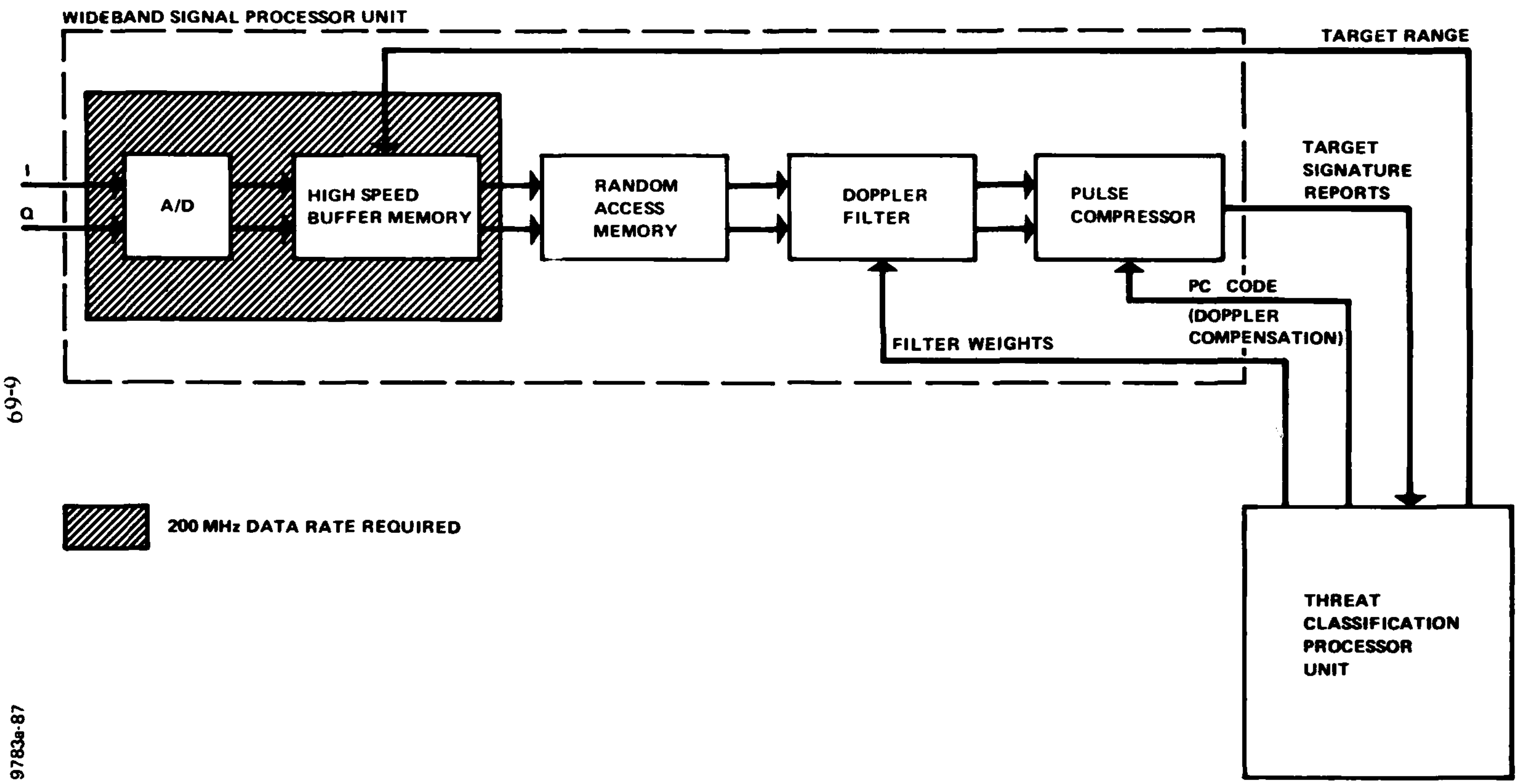


Figure A. Simplified block diagram of the wideband signal processor

Technology Development Requirements for A/D Converters

Even though significant improvements in A/D converter technology are likely to occur by 1985, a 400 MHz conversion rate at six-bits can probably best be met in that time frame by multiplexing a number of lower performance units together; e.g., four 100 MHz units or eight 50 MHz units. This can be contrasted with the availability today of a monolithic LSI converter capable of converting 6-bits at 30 MHz (TRW TDC10145).

The technical literature provides references to several R&D programs which have produced laboratory models of very high performance A/D converters. These include[1], for example, A/D converters which are capable of the following:

- 4 bits at 100 MHz
- 3-bits at 200 MHz

The literature also contains projections for significant improvements over these figures. These projections are based on several different R&D programs using a wide variety of technologies including silicon, GaAs, transferred-electron devices (TED), and electro-optical.

A high-speed, high-performance (6 bits at 400 MHz) analog-to-digital converter must be developed in the 1985 time frame to meet the wideband signal processing requirements for the ATR target signature processing.

Technology Development Requirements: High-Speed Memory and Logic

The high-speed memory and logic requirements of the Wideband Signal Processor will require gigabit switching speeds for the basic logic circuits. Gallium Arsenide (GaAs) integrated circuit technology currently under development, is projected to be the most likely technology for achieving these switching speeds. At present, the level of integration density achieved using this technology is comparable only to SSI and the less complex MSI functions. By 1985, production capability in GaAs is forecast to be available with 0.5-micron features, 5-GHz clock rates and up to 500 gate complexity. During the 1985-1990 period, 10-GHz clock rates and 2500 gate complexity has been forecasted. If these projections are to be met, however, the present limitations of GaAs materials processing must be successfully overcome.

Technology development of a dense, high-performance (1K-bit at 50 MHz to 100 MHz) shift register memory chip will be required to meet the specific requirements of the High-Speed Buffer Memory for wideband signal processing.

Technology Development Candidates

Specific candidates for technology development which would be useful for wideband signal processor applications are summarized in Table I.

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[1]B. G. Bosch, Gigabit Electronics – A Review, March 1979, Proc of the IBBB, Vol 67, No. 3, pp. 340-379.

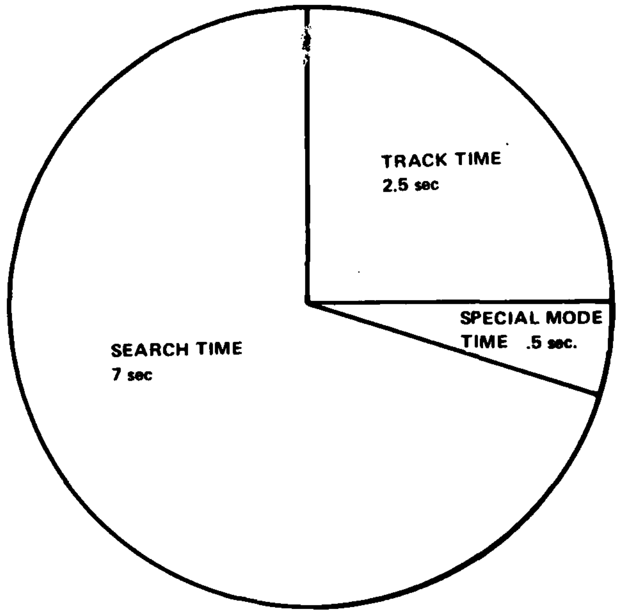

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Figure B. Special mode time provides 20 periods of 25 msec per period every 10 sec.

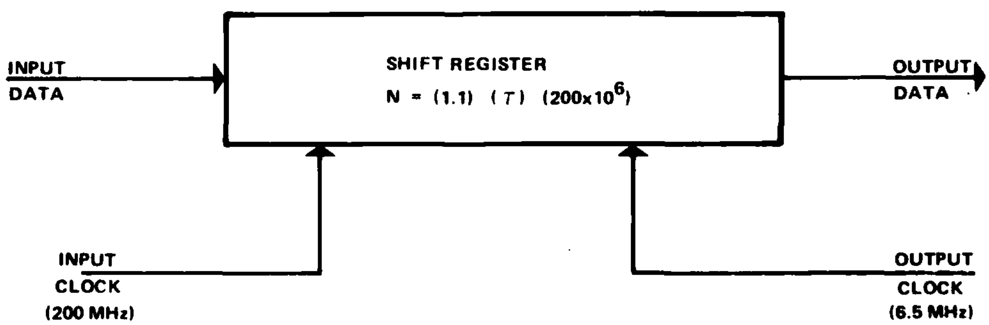

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Figure C. Use of a high speed N-bit shift register memory to capture 200 MHz data centered about a pulse of τ μsec duration.

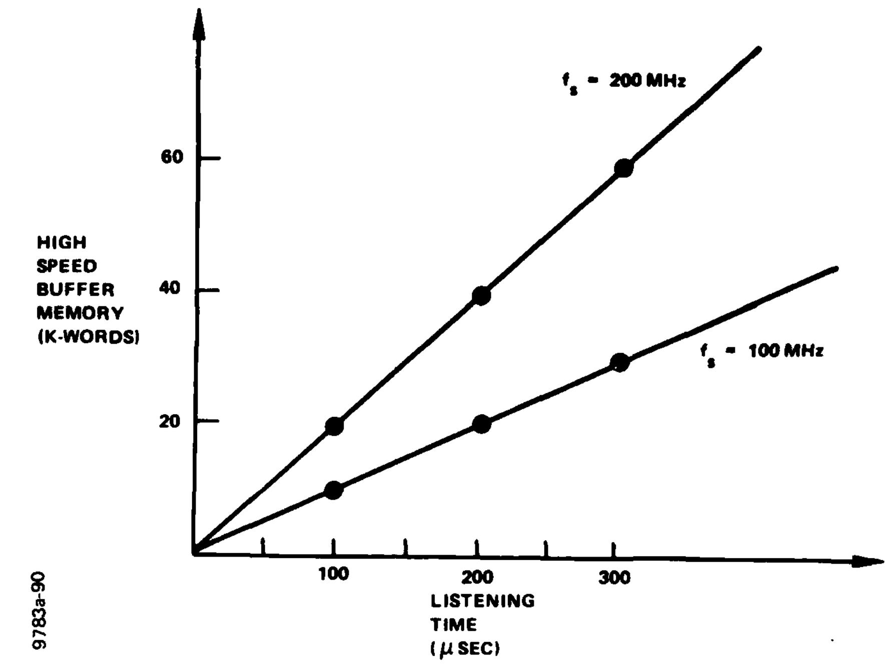

Figure D. High speed buffer memory requirement as a function of listening time and sample rate (i.e., time-bandwidth product)

Table I. Technology Development Candidates for Wideband Signal Processing Applications

Candidate	Performance
A/D Converter	6-bits at 400 MHz (desired) 6-bits at 100 MHz (acceptable)
Shift Register Memory	1K-bits at 400 MHz (desired) 1K-bits at 100 MHz (acceptable)
Uncommitted Logic Array	500 gates at 2 GHz

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6.4.7 RISK ASSESSMENT

Based on the assumption of a continuing study/development program through 1985, most signal and data processing requirements are likely to be met.

This section addresses the overall risk assessment of meeting the performance, weight and volume requirements which have been established for the processor subsystem for the post-1985 time frame. (See Table opposite).

In each case the assessment is based on a continuing study/development program through 1985 of sufficient magnitude to define all system and subsystem parameters iteratively against the background of a developing technology. In addition, it assumes the specific development of the technology candidates identified in the Table and described in more detail elsewhere in this report, or their equivalents, if the evolving technology should favor alternative architectures.

Under these assumptions, signal and data processing requirements can likely be met in th 1985 time frame with a low to medium risk. Weight and volume constraints are likely to be continuing problems, however, since increased system definition usually leads to signal/data processor growth.

The risk of meeting the wideband signal processing requirements by 1985 is judged to be high.

Risk Assessment of Meeting Performance Requirements in the 1985 Time Frame

		Impact of 1979 Technology		Applicable 1985	
		Performance	Weight and Volume	Technology Development Candidate	Risk Assessment of Meeting Performance, Weight, and Volume Constraints by 1985
Signal Processor Functional Requirements	Analog/Digital Conversion	Marginally Acceptable	Excessive	A/D Converter 11-Bit at 6.5 MHz	Low Medium Risk: Some development required; several military programs will require similar function
	Doppler Spectral Filtering	Marginally Acceptable	Excessive	Memory (RAM) Chip Size: 16K X 1 Cycle Time: 75 nsec Power: 0.05 mw/bit	Low/Medium Risk: Some development (MIL environment) required; commercial market should provide sufficient demand for memory;
	Pulse Compression	Marginally Acceptable	Excessive	Digital Correlator Size: 512-Bit Clock: 6.5 MHz Power: 6 mw/bit	Medium Risk: Special Development required; DOD VHSIC Program could contribute
Data Processor and Control Functional Requirements	Processing/Control Functions	Acceptable	Excessive	LSI Uncommitted Logic Arrays: Size: 1000 Gates Clock: 6.5 MHz	Low/Medium Risk: Development required; VHSIC Program specifically addresses this area
Wideband Signal Processing Functional Requirements	Analog/Digital Conversion	Unacceptable	N/A	A/D Converter 6-Bit at 100 MHz	High Risk: Development required; lab models likely
	High-Speed Memory	Unacceptable	N/A	Shift Register Memory 1K-Bit at 100 MHz LSI Uncommitted Logic Arrays Size: 500 Gates Clock 2 GHz	High Risk: Development required; lab models likely High Risk: Development required; lab models likely

6.5 MECHANICAL TECHNOLOGY

6.5.1 MECHANICAL DESIGN CONSTRAINTS

The tactical environment will impose severe constraints upon the mechanical design of the ATR.

The operational requirements for the future TACS and all of its elements dictate the need for an ATR composed of small, flexible, modular units that will:

a) Decrease ATR vulnerability by decreasing the value of its individual elements and make each element easier to move and/or conceal.

b) Adapt the ATR to the current situation (terrain, jamming, etc.) and accommodate degraded status situations (component failure, physical damage, etc.) as quickly as possible.

c) Assemble and quickly deploy a radar sensor system tailored to the specific needs of the contingency and theater of operations (360° or sector coverage, monostatic or bistatic, etc.).

Tactical deployment of the ATR will entail transport to the theater of operations as military cargo. Tactical mobility will be required on short notice after arrival. Vibration and shock associated with transport/mobility will constrain packaging techniques and the overall structural configuration. For example, components of the antenna subsystem must possess resonant frequencies above those experienced or be isolated from them. Components of the Receiver/Processor subsystems, must employ large-scale integration, large bulk memories, etc. They must also be densely packaged and reduced in size to effect subsystems that are more inherently shock and vibration proof. The mobility requirement additionally imposes a weight constraint that demands mechanical design simplicity and effective materials usage.

The tactical environment includes the threat of physical damage from a variety of weapons systems. The effects of these weapons systems range from small projectile fragments to nuclear blast. There are several generally recognized methods of decreasing vulnerability/ improving survivability; most notable among these are hardening, redundancy, and mobility. The latter two can be achieved by selecting the proper configurational design for the system and the former by providing the degree of hardening (protection) needed.

The significant mechanical design constraints/requirements are shown in the Table opposite.

Mechanical Design Constraints/Requirement

Requirements	Baseline Design
Modular Units	3 modular units: 2 identical radar sensor units, 1 prime power unit.
Redundancy	Provided by two identical radar sensor units. Increased redundancy can be provided by configuring system as four single antenna face sensors with integral prime power.
Transportability/Mobility	Achieved by modular design.
Hardening	Achieved through use of armored vehicles and armored antenna faces.

6.5.2 BASELINE MECHANICAL DESIGN

The ATR achieves high mobility through deployment with three self-propelled vehicles.

Three vehicles carry the full ATR – that is, an ATR that covers a full 360° azimuth sector. The four antenna faces are mounted on two vehicles as shown in the Figure.

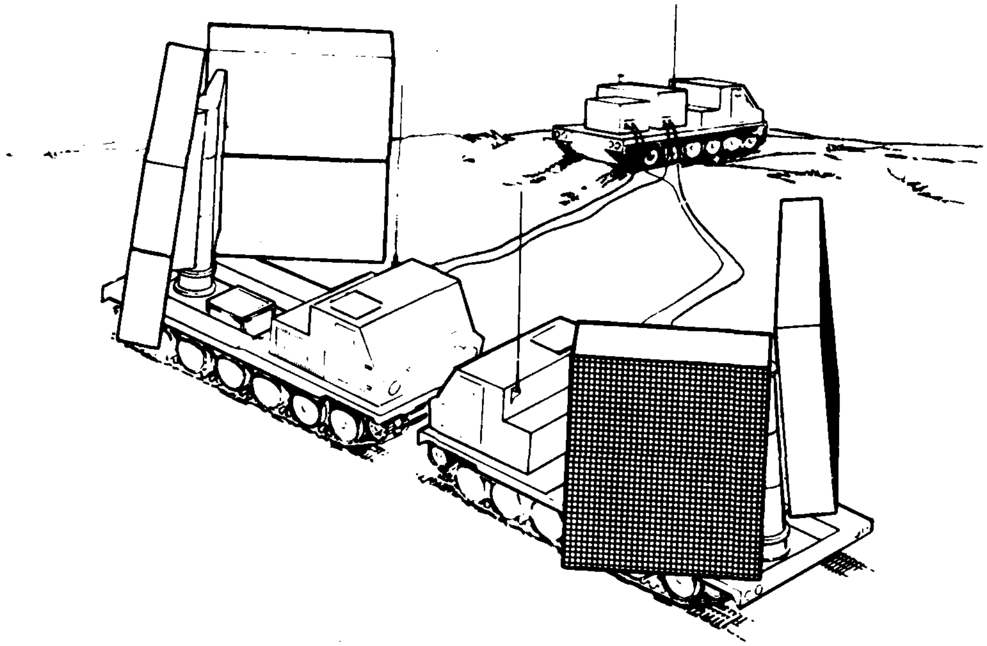
The vehicle selected for carrying the radar sensors is the GSRS carrier with minor modifications to the cargo area. A weight breakdown is shown in Table I. The signal/data processors are mounted in the cargo well of the vehicle. The armored crew cab of the GSRS is of adequate size to contain a CRT display communications equipment and operator. Prime power, timing and control and the System Processor are contained on a second vehicle which can be an M548 Carrier, a smaller carrier than the GSRS. There is adequate capacity on this vehicle to also carry fuel.

It is possible to set up and tear down this configuration with the use of three men in the time allocated (i.e., 15 and 5 min., respectively). However, the combination of vehicles will allow a crew complement of 6 to 9 men dependent upon number of radar sensor modules deployed.

Prime power is a motor generator set mounted to its own vehicle, M548 cargo carrier. Fuel can also be carried on this vehicle.

To achieve off road mobility, the antennas are moved to vertical relative to the vehicle, placed back to back and secured to the vehicle at their bases. Highway transport will require that the upper halves of the antennas be removed and secured to a trailer. This may require that the antenna vehicle carry its own hoist provisions.

To level the antennas, there is a gimbal frame mounted in the bed of the vehicle. There is also a pedestal, integral with the gimbal, so that the antennas may be moved from 90° opposed position to the back to back position.



- TWO GSRS CARRIERS – ONE M548 CARRIER
  - TWO RADAR SENSOR VEHICLES
  - ONE PRIME POWER/FUEL VEHICLE
- FOUR PLANAR ARRAYS
  - 276 X 171 ELEMENTS (13.3 ft X 12 ft)/ARRAY
  - 8562 lb/ARRAY
- TOTAL ANTENNA PAYLOAD 18,624 lbs
- PRIME POWER REQUIRED 100 kW
- COMPOSITE TECHNOLOGY UTILIZED

ATR baseline configuration

Table I. Weight Breakdown Baseline Configuration

Horizontal Feed with Lens	43 lbs	
Azimuth Switch (2 each)	3 lbs	
Phase Shifter	1 lb	
Amplifiers (average)	7 lbs	
	54 lbs x 138	= 7452 lbs
Elevation Lens		+10
Cabling		+300
Active Elements		= 7762 lbs
Structure 800 lbs		800
Array Weight		= 8562
		x2
		17124
Signal/Data Processor		200 lbs
Leveling and Erection System		900 lbs
Vehicle Stabilization		600 lbs
		18824 lbs
Payload GSRS		20000 lbs

6.5.3 MECHANICAL DESIGN TRADEOFFS

There are a number of mechanical design tradeoffs to be considered; all of which will affect the ATR design and performance.

Utilizing a standard width vehicle will require stabilization. The GSRS may require less stabilization due to the availability of a suspension lockout system. It will be necessary to incorporate a leveling system between the vehicle and the antenna or the ATR will require a flat and level site thus reducing freedom of deployment. The leveling of the vehicle with antenna erected, while simple in concept, will require additional power or increased time for set up. Also larger pads must be provided to limit soil loading.

Prime power is another area of consideration. The baseline employs a diesel powered motor generator set. It may prove to be more efficient to run the generator from the prime mover engine although such engines have not been noted for being entirely suitable for long term, steady speed operation. There are turbine generator power units available that may require extensive quieting to be usable. Identification of the fuel to be most available could be a problem. Possibly incorporating an engine with multi-fuel capability such as a turbine will be part of the answer.

Other tradeoffs regarding materials, mobility and survivability will be addressed in the respective sections.

6.5.4 MATERIALS TECHNOLOGY

From the mechanical design point of view one area of concern in the antenna is that of assuring the high order of accuracies and stability demanded by system functional performance requirements. At the same time the system must be lightweight, mobile, easily deployed and resistant to the tactical environment.

Much work has been done in the area of lightweight, stiff structural components by the aerospace industry. Weight efficiencies of various structural materials are shown in Figure A. Utilization of one or a few of these materials, as deemed appropriate, could minimize the elastic deformation of the antennas structural elements under severe loading conditions while resulting in a lightweight, mobile design.

Unlike metals, designs with advanced composites begin on the matrix/reinforcement level. Tradeoffs between fiber properties, fiber orientation and matrix properties can be used to optimize the material for a specific application. On the plot of specific tensile modulus versus specific tensile strength (Figure A) a particular composite permits various combinations of specific properties by variations in orientation of the specific fibers. Mixing fiber types in the reinforcement further widens the material characteristics available. Some blends of graphite and Kevlar are presently available.

Further advances are being made in the composites of an aluminum matrix with boron fibers. Boron nitride fibers for use in a resin matrix are being developed by Carborundum Co. with Air Force support. The primary intent of this effort is to fabricate a lower loss radome.

In the area of armor, work is underway on a microwave transparent armor material called XP film. Processing requirements limit wide use at this time.

Resin matrix composites have had a moisture absorption problem that has limited their efficiency. Structural properties of the composite materials on the Navy F-18 fighter were downrated for design purposes while still resulting in significant weight reductions. Solutions to this problem are underway in the area of matrix modification. Orders of magnitude improvement in both shear and flexural strength have been achieved with a high-vinyl modified epoxy resin being developed by the Air Force Materials Laboratory.

Resistance to elevated temperatures has been one of the constraints on many uses of resin matrix composites. This is being alleviated to some degree by the introduction of higher temperature resistant polyimide resins. There are some quality control problems but these are being studied by the aerospace industry with NASA support through the ACEE program.

The preliminary baseline design incorporates an extensive amount of advanced composite material to reduce the weight of the antenna and provide armor protection. For example, the stripline feeds have honeycomb core dielectric with Kevlar backed aluminum

ground planes. This design, while strong and compact, creates a heat removal problem due to the resistance to heat flow. The lenses are solid state construction with a high K dielectric and Kevlar backed aluminum ground planes. Construction of both of these units incorporates multiple layers of adhesive. It is necessary to increase the heat flow rate from these assemblies. One method would be to decrease the temperature of the area around the component by air conditioning of some nature.

The electronic components are solid state and densely packaged. The use of heat pipe technology, vortex tubes or other means to increase rate of heat flow may be required.

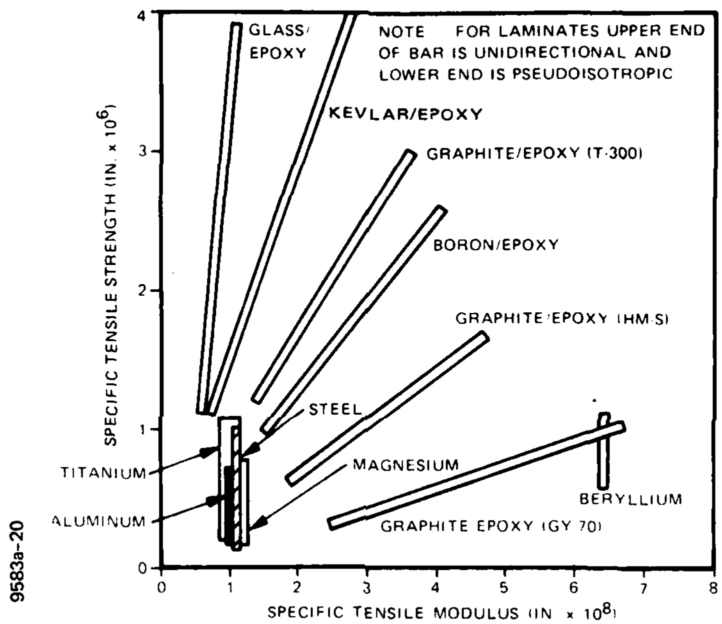


Figure A. Comparison of weight efficiency for various structural materials

6.5.5 MANUFACTURING TECHNOLOGY

Acquisition cost for any system of this type is heavily influenced by fabrication costs; therefore, production methods will be an important factor.

Since the preliminary concept for the antenna portion of the system has been based on the use of composite materials and the overall cost of parts using these materials depends on the cost of tooling and labor, significant attention must be paid to these areas.

Considering the stringent accuracies required of the antenna, control of warpage in the component is of prime importance. Most critical components may have to be fabricated on steel tools while less critical components can be fabricated on aluminum tools. Labor costs can be controlled by detail design factors and extensive use of tooling aids.

Most of the tooling will be of fairly simple nature. Flat surfaces with critical dimensions controlled by material thickness dimensions will predominate. One of the critical areas will be in the stripline feed assembly. Here the impedance of the assembly is controlled by dimensional control of the thickness of the honeycomb dielectric. This dimension is normally controlled within plus or minus 0.006. The entire assembly can be fabricated in three steps. First is fabrication of the printed circuit on a three to five mil substrate. Second, fabrication of ground planes by bonding aluminum foil to Kevlar reinforcement. Finally, secondary bond previous components to honeycomb with scrim supported adhesive. Flatness of ground planes will be assured through use of flat tooling for bonding aluminum to the Kevlar. Dielectric spacing is controlled via machining of honeycomb and final assembly tolerances are assured by use of flat plate presses.

6.5.6 MOBILITY AND TRANSPORT

Rapid set up and "march order" moves are possible by allowing the antennas to remain upright and limiting intravehicle cabling.

Field mobility is possible with the antennas erected with limitations imposed in traversing side hill slopes due to the high center of gravity of the vehicle/antenna assembly in this configuration. To become mobile, it will be necessary to disconnect the intervehicle cabling, move the antennas to vertical relative to the vehicle, swing the antennas back to back and lock them to the vehicle.

Highway transport will require that the upper half of each antenna be disconnected and removed to a trailer to be towed.

To achieve transport by rail or air it will be necessary to remove both antennas and break them in half. The antenna portions must then be placed on pallets for transport.

A search was made for shock and vibration data during various modes of mobility and surface transport. Vibration data ranges from 1.5g at 2 to 7 Hz to 20g at 180 Hz. Shock data ranges as high as 20g at 20 msec pulse.

MOBILITY FIELD

- WITH ANTENNAS ERECTED LIMITED

TRANSPORT – HIGHWAY

- WITH UPPER ANTENNAS STOWED ON TRAILER – 8 ft WIDE X 10.5 ft HIGH
  - MEETS REQUIREMENT U.S. AND EUROPE

TRANSPORT RAIL

- ANTENNAS REMOVED FROM VEHICLE, DISASSEMBLED AND PALLETED
- ADEQUATE CLEARANCE U.S. AND EUROPE

TRANSPORT AIR

- ANTENNAS REMOVED FROM VEHICLE, DISASSEMBLED AND PALLETED
- ANTENNAS WILL FIT C-123B, C-124C, C-130A, C-133A, AND C-5A
- VEHICLE LIMITED TO C-124, C-133A, AND C-5A

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Mobility and transportation of the tactical radar is possible due to its modularity.

6.5.7 SURVIVABILITY

A large part of the hostile tactical environment is the threat of weapon effects. These range from small projectile fragments to nuclear weapon blasts. Various levels of protection are available with attendant various levels of impact on cost and weight.

Vulnerability of all the system components to all aspects of the threat must be assessed. Methods and levels of protection can then be specified based upon the level of vulnerability. Some of the methods include:

- Hardening by design and materials
- Incorporation of armor
- Redundancy of components and structure
- Improved repairability
- Shielding

Protection from ballistic fragments is provided by armor. Traditional armoring techniques required the use of heavy aluminum or steel plates. Lighter weight armor materials have been developed. Several of these are woven Kevlar and XP film. The XP film (expanded polypropylene) should be used for nonstructural applications only. It is mentioned because of its unique electrical properties which make it suitable as a radome while providing protection from projectile fragments.

Kevlar, as an armor, has proved to be quite successful. In a semirigid formulation of one-half inch thickness can provide protection against, for example, a 207 grain fragment with a velocity of about 2,000 feet per second.

Higher levels of protection are achievable by combining different materials so as to offset their respective weak points. A typical two-component armor system consists of a facing of a hard, brittle material and a backing of a softer, ductile material such as semirigid Kevlar (see Figure A). The projectile or fragment is broken upon impact with the hard facing in the first few microseconds after contact. The residual energy and the smaller fragments are then absorbed by the backing material. Performance of such a combination is shown in Figure B.

A nuclear weapon blast has a number of effects. These include EMP (Electromagnetic Pulse), airblast wave, thermal radiation, ionizing radiation, and radioactive fallout. Vulnerability of the system to any of these threats must be assessed.

EMP may affect the internal circuitry and components. Partial protection can be provided by use of electromagnetic shielding techniques but the exposed radiating face cannot be so shielded.

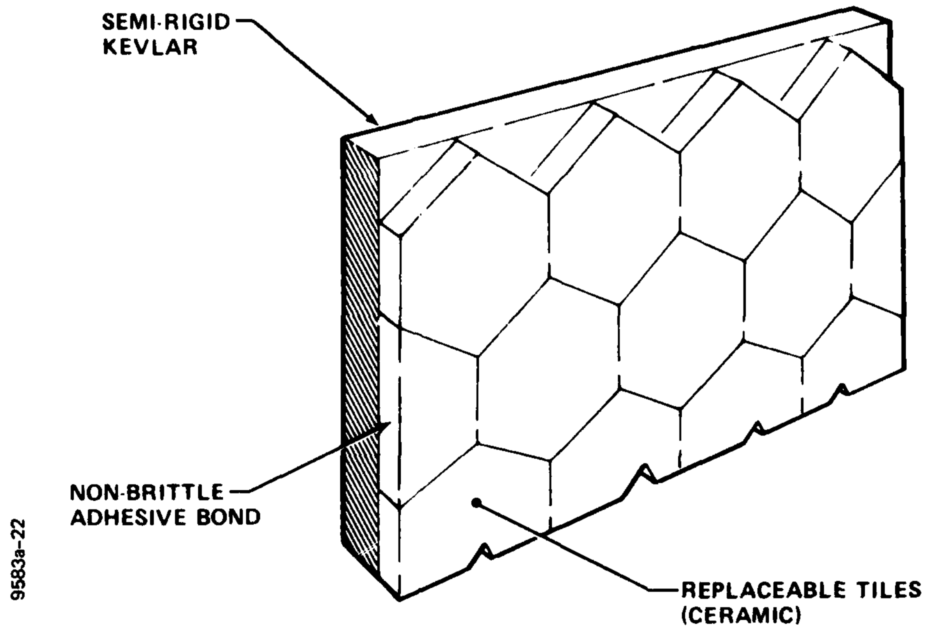

Figure A. High energy fragment and ballistics armor

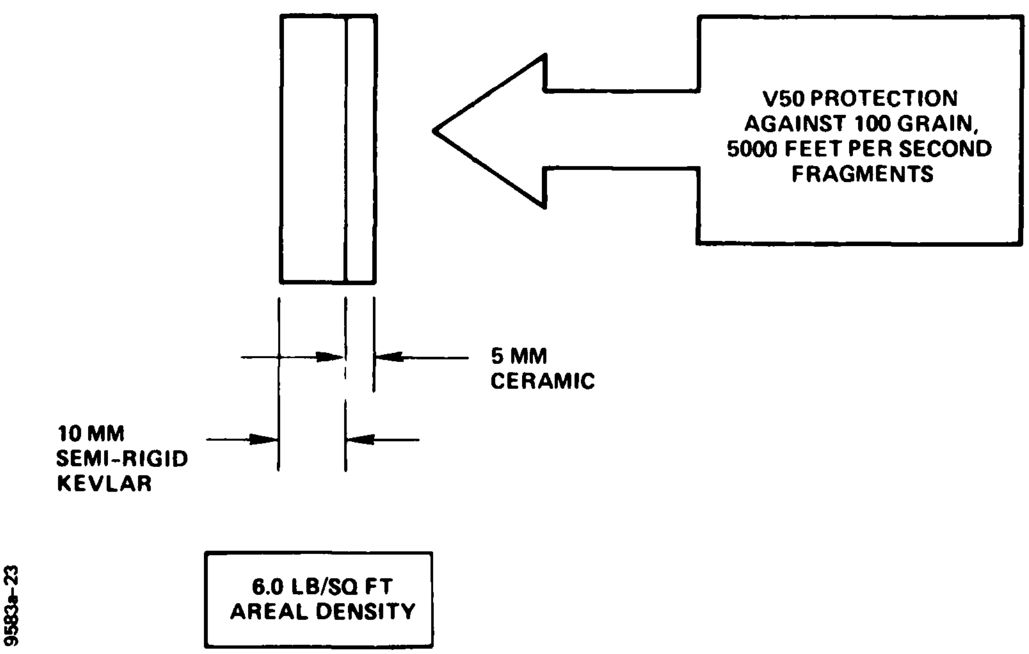

Figure B. Estimated capability of two-component armor

Air blast wave results in wind effects that may greatly exceed the elastic limit of the antenna structure. This air pressure may greatly exceed that resulting from wind depending on range from ground zero. Level of survivability must be defined. In this area high structural efficiency will alleviate disastrous weight increases.

Thermal radiation will tend to destroy the composites matrix through reducing the structural integrity in relationship with the char depth. Protection can be provided for short periods of time by utilizing an intumescent coating. Again the radiating face may not receive protection because electrical characteristics of the coating may not be adequate for radome use. There is an intumescent coating commercially available that will protect steel up to 1000°F for one hour. The ultimate heat resistance in a polymide resin matrix is in the area of 500 to 600°F. Thus, a like thickness of coating could possibly protect a composite structure for thirty minutes.

The effects of ionizing radiation on the resin matrix is variable. Some resins are degraded and others are strengthened through further crosslinking of the molecule chains. Thus, it will be necessary to restrict freedom of choice of resin matrix.

6.5.8 MECHANICAL TECHNOLOGY ASSESSMENT AND RISK

Successful achievement of a cost effective ATR system will depend upon a balanced approach to all of the requirements of the tactical environment.

Weight affecting mobility must be balanced against survivability in the tactical mobility and transportation modes of operation. Performance levels must be balanced against manufacturing costs incurred to achieve these levels. Reasonable performance parameters must be established in the area of performance, mobility, transport and survivability for the ATR system to assure maximum performance vs system cost.

Certain technological areas associated with production of the antenna will need further development.

At present, these technological items are available:

- The GSRS Carrier with a 20,000 lb payload.
- The M548-S Carrier with a 16,000 lb payload.
- Manufacture of controlled impedance stripline sandwich assemblies.

For the future, these technological items should be accomplished:

- Transfer of aerospace composites technology across to the radar industry via exploitation of the NASA/ACEE data bank.
- Reduce production costs of stripline feed/integral lens production by better tooling/production techniques.
- Develop lighter weight armor. This is currently being investigated by a number of firms and some improvement may be forthcoming. At present the ceramic/kevlar combination referred to earlier is the lightest available.
- Increase passive heat transfer capabilities. The heat pipe industry may be able to achieve considerable improvement.
- A tactical assessment of the threat resistance threshold required should be conducted in these areas.
  - EMP level resistance
  - Airblast
  - Thermal Radiation
  - Ionizing Radiation
  - Fragment size and velocity
  - Radioactive Fallout

- Adaptation of vehicles to accommodate equipments in the area of structural wiring and shock/vibration provisions.
- It may be advisable to develop alternate feedstocks for the oil based resin matrices presently used in advanced composite structures. Alternately it may be necessary to secure an oil allocation to allow fabrication of the advanced composite raw materials.

Time and Cost Estimates

Item	Labor and Materials	Calendar Time	Risk
Composites Technology	40 man-months $222,000 materials	24 Months	Low
Data Search Process Specifications Test Hardware Configuration Fabricate Test Items Test and Reduce Data			
Stripline/Lens Production	6 man months	12 Months	Low
Design & Development Tooling Design			
Lighter Weight Armor	$150,000 material	18 Months	Med
Define Several Configurations Ballistic Tests Refine Final Configuration Final Test & Data Reduction			
Threat Resistance Threshold	40 man-months $ 20,000 material	10 Months	Low
Consultation Matrix Generation Matrix Reduction Threshold Definition			

Section 7

RELIABILITY AND COST CONSIDERATIONS

7. RELIABILITY AND COST CONSIDERATIONS

7.1 RELIABILITY

The baseline ATR has been designed to have a high level of reliability through the use of redundant solid-state power amplifiers, and extensive use of BITE and Monitoring.

The worst case reliability prediction of the baseline ATR system is provided in Table I. The predicted reliability was arrived at in accordance with procedures of MIL-STD-756. Antenna array parts temperatures were assumed at 70 degrees centigrade and the following component and unit criteria were assumed:

a) Microcircuits shall be MIL-M-38510, Class B, to the degree of availability and all devices screened to MIL-STD-883, Level B.

b) Semiconductors shall be JANTX quality level.

c) Passive parts (resistors, capacitors, etc.) shall be Established Reliability (ER), Level P or better

d) Other parts shall be either MIL specified or controlled for quality assurance through parts and component specifications.

The baseline system reliability prediction considers redundancy at various equipment levels and multiple maintenance time periods. The following paragraphs discuss the redundancies considered.

Antenna RF Solid-State Power Amplifiers

The four antenna faces would contain 552 amplifier sets which would contain an estimated 20 thousand microwave transistors. A set of modules powers one row of horizontal radiators. Each of the 552 sets contains one to ten modules, to form the amplitude taper in the vertical plane. Allowable soft degradation (performance degradation that does not fall below the required performance level) exists such that transistors redundancy plus module (each of the 552 amplifier sets contain one to ten modules) redundancy could be considered. In the projected baseline design, each module contains one series transistor, driving seven parallel transistors. One of the seven transistors can fail without module failure, so six of seven redundancy exists (see Figure A).

The redundant equivalent failure rate of the transistors was calculated using a maintenance time of six months which would allow for a maintenance program that would require replacement of noncritical transistor failures no more often than twise a year. Allowable soft degradation redundancy is a necessity in the transmitter and can be accomplished by two methods. Either extra amplifier sets can be provided or an extra module can be added to the amplifier sets. Either approach will achieve soft degradation redundancy. Figure B contains the reliability block diagrams for the two configurations. The reliability analysis disclosed that a combination of the two approaches optimized the redundant failure rates and was a function of the number of modules contained in an amplifier set. A maintenance time of 168 hours is used in the reliability analysis.

Table I. Baseline System Reliability Prediction

Item	Qty	Failure Rate ($f/10^6$ hrs) Unit	System
Antenna/Transmitter	4	86.821	347.284
Signal Processor	5	191.862	2.931*
Data Processor	5	355.599	10.030*
Receiver/Processor Power Supply	4	1.8227	7.291
Frequency Synthesizer	1	18.979	18.979
Timing and Control	1	25.582	25.582
		Total FR =	412.097
		MTBF =	2426 hours

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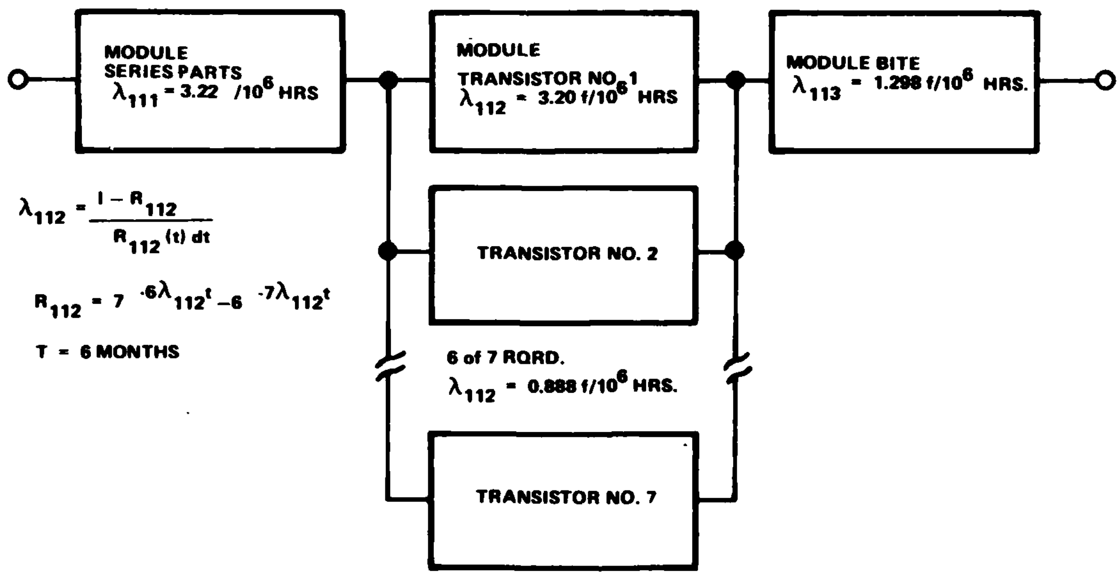
*Redundant equivalent failure rates.



$$\lambda_{112} = \frac{1 - R_{112}}{R_{112}(t)\,dt}$$

$$R_{112} = 7^{\,-6\lambda_{112}t} - 6^{\,-7\lambda_{112}t}$$

T = 6 MONTHS

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$$\lambda_{11} = \lambda_{111} + \lambda_{112} + \lambda_{113} = 5.406\ f/10^6 \text{ HOURS}$$

$$R_{11} = e^{-\lambda_{11}t} = e^{-(5.4\times10^{-6})t}$$

Figure A. Module reliability block diagram and math model.

Antenna PIN Diodes and Drivers

Contained in four antenna arrays (Faces) are an estimated 295,000 PIN diodes which could present an undesirably high failure rate. This potential problem can be resolved by the use of quad-network pin diodes (four pin diodes to a package or chip with two in series and two parallel paths) to provide adequate diode redundancy. This redundancy will yield at least a twenty-to-one reduction in individual pin diode failure rates with no redundancy maintenance required during the life of the antenna. In addition, allowable soft degradation in inherent in the pin diode switching and driver circuits which allows for m of n redundancy in pin diode circuits. These redundancies are considered in the reliability prediction. As in the transmitter analysis, the maintenance time used for the m of n redundancies is 168 hours.

Antenna RF Connections

In addition to the microwave transistors and the pin diodes, a very large quantity of RF connections must be considered as they could significantly affect antenna reliability. The reliability prediction therefore assumed that hard wiring (no RF connectors) would be used in the equipment where no redundancy from allowable soft degradation existed. This assumed design approach is considered necessary to achieve high reliability in the antenna.

Antenna BITE and Monitoring

Throughout the antenna, sufficient BITE and Monitors are included in the design and their inclusion is considered in the reliability analysis. Normally, the BITE and Monitors are a part of the individual redundant items (i.e., each amplifier set and module contains individual BITE), and their failure rates are considered in the redundant reliability determinations. A centralized Performance/Fault Isolation assembly is included in the antenna and it is considered necessary to provide a voting type redundancy in this assembly.

Signal Processor

The system contains five Signal Processors: one per antenna face and one spare. Each Signal Processor consists of channels of initial processing. Redundancy exists because only 10 channels of the 11 are required for mission success. The reliability prediction considered the 10 of 11 redundancy with eight hours between card failure and card replacement.

Data Processor

There were no internal redundancies required or considered.

Processor Low-Voltage Power Supply

For every two low-voltage subassembly power supplies, a redundant item is necessary and is assumed in the radar reliability prediction. The maintenance schedule for replacing failed redundant power supply items was assumed to be six months (4380 hours).

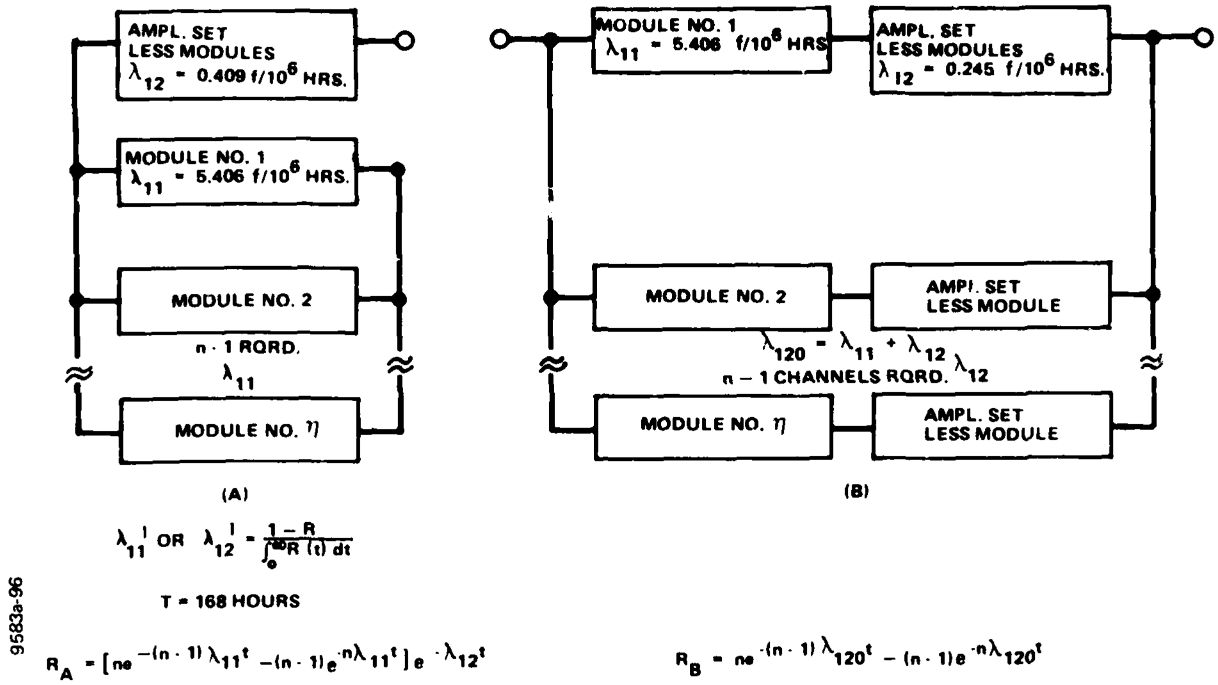


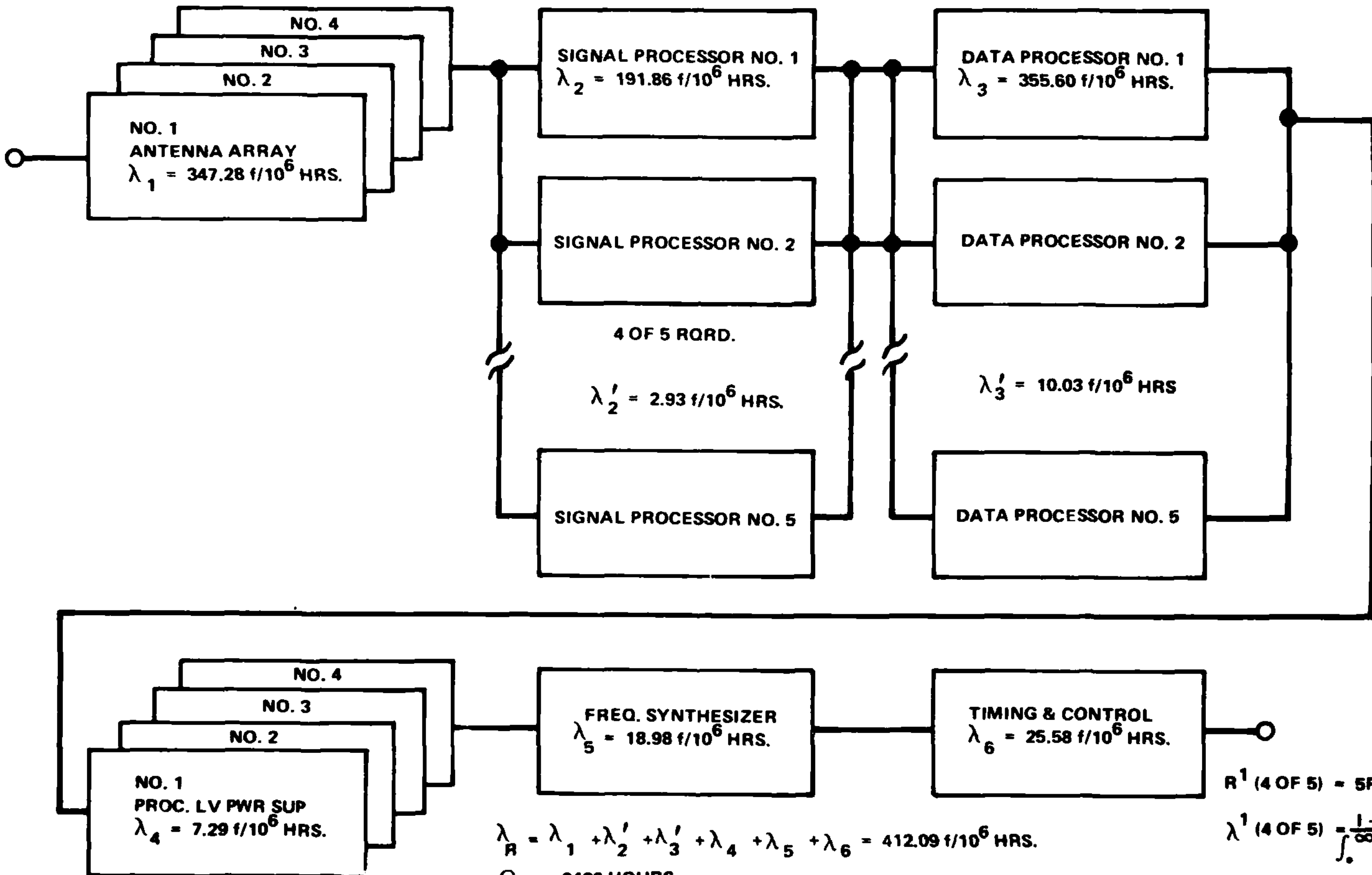
Figure B. Amplifier redundancy configurations.

Frequency Synthesizer, and Timing and Control

There were no redundancies considered.

In addition to redundancies discussed in the foregoing for the system elements, the reliability prediction considers a redundant signal processor a redundant data processor exist in the system. Figure C contains a reliability block diagram of the system which shows the four of five redundancy (active type) for the signal and data processors. The math model for the redundancies is provided, and for the model "t" equals eight hours.

The achievement of the reliability level reported herein can be accomplished through: the selection and application of reliable parts and components, packaging techniques for minimization of parts used, and the incorporation of optimized designed-in redundancies. To enhance the potential reliability achievements, and possibly achieve further gains, there are three areas of pursuit for future reliability improvements: (1) the improvement of the reliability characteristic of microwave transistors for the C-band application is thought to be a significant and desirable challenge; (2) phased array antennas can use very large quantities of pin diodes, therefore the pursuit of very high reliability pin diode and driver circuits appears to be in order; and (3) RF connectors may also be used in large quantities in the phased array antenna, and the large potential effect of these parts failure rates may be reduced through high-rel connectors or developed techniques for RF connections not using the connectors.



R^1 (4 OF 5) $= 5R^4 - 4R^5$

λ^1 (4 OF 5) $= \dfrac{1 - R^1}{\int_0^{\infty} R^1(t)\,dt}$

$\lambda_R = \lambda_1 + \lambda_2' + \lambda_3' + \lambda_4 + \lambda_5 + \lambda_6 = 412.09$ f/10^6 HRS.

$\Theta_R = 2426$ HOURS

$R_R = \varphi^{-\lambda_R t} = \varphi^{-0.000412t}$

Figure C. Baseline system reliability block diagram and math model.

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7.2 COST

The goal of this study has been not only to synthesize a conceptual radar system that meets the specified operational performance in a hostile TACS environment, but also provides the lowest possible cost over the life cycle of the radar.

The stated goal of this study has been to synthesize a conceptual radar system which will meet the specified operational performance requirements in the presence of ECM, chaff, ARM, and clutter environments anticipated in the post-1985 time frame. However, it is not enough to simply meet the real-time operational performance requirements; the system must also demonstrate an operational availability consistent with the needs of the user at the lowest possible cost over the life cycle of the hardware.

The required short-term dependability of a system can be achieved through the use of high reliability components and/or selective redundancies. The longer term availability of the system requires the ability to detect and repair any given fault in the shortest possible time period. This maintainability feature can be achieved through extensive use of automated fault detection/isolation circuitry, careful attention to the packaging/modularity design of the hardware, and the establishment of an effective maintenance support system.

In the final design of any complex radar system, careful attention must be given to reliability, maintainability, and supportability. All three factors directly influence the operational availability and life cycle support costs of the system. Numerous trade-off studies must be conducted to ensure the most cost-effective approach.

Life Cycle Cost Factors

Life cycle cost (LCC) is defined as "the total cost to the Government for acquisition and ownership of a system over its full life. It includes the cost of development, acquisition, operation, support, and, where applicable, disposal." The most significant cost elements in the total LCC are:

a) Development and production costs
b) Maintenance (labor and transportation) costs
c) Investment in spare line replaceable units (LRUs)
d) Investment in spare piece parts
e) Investment in consumable LRUs
f) Investment in support equipment
g) Cost of maintenance and operating facilities
h) Cost of personnel training
i) Cost of all maintenance documentation
j) Cost of inventory management
k) Cost of software maintenance.

Cost element a), development and production, is an acquisition cost element. The remaining elements constitute the ***maintenance efforts*** which reflect the cost impact of the system design.

General Design Considerations

Three design factors which significantly affect LCC are modularity, commonality and BITE.

a) **Modularity** – Generally, increasing the modularity of an equipment by subdividing higher order assemblies improves the LCC characteristic. The improvement is most evident when the subdivision results in accumulation of the high-failure-rate parts on a single LRU. This permits a spares policy of stocking spare LRUs for high-failure-rate LRUs, and selective stocking (or nonstocking) of spares for other (low-failure-rate) LRUs. Furthermore, since smaller LRUs have fewer parts, they tend to be less expensive. Thus, the unit cost of a failed LRU is lower; the cost of the replacement spare is lower; and the unit and total cost tied up in ***maintenance float*** spares is lower.

   There are limits to the benefits of increasing modularity. However, one such limit is BITE. If a functional unit has a required MTTR of 10 minutes, then the individual modules making up that unit should have sufficient BITE to permit identification and replacement of each failed module in 10 minutes, average. Consequently, the benefits of increasing modularity require careful consideration of the potential increase in cost anc complexity of BITE, to assure a cost-effective overall solution.

b) **Commonality** – There are no negative aspects to ***true*** commonality. That is, the use of common items in functional applications that are identical or sufficiently similar to make effective use of the item.

   Commonality should be considered at the systems level as well as at the parts level to reduce the types of LRUs to the lowest practical number. However, the compromises that occur to obtain commonality, in unequal applications of an item, must be carefully weighed to verify that they are cost effective.

c) **Built-In Test Equipment (BITE)** – BITE design that determines the ease with which faults are indicated, localized and tested after repair, also influences support costs associated with personnel skills, personnel requirements, and both common and special-purpose test equipment requirements. BITE design is critical to the attainment of guaranteed maintainability properties of an equipment and also influences the distribution of repair times. The repair time distribution is used to calculate a risk for shortage which determines spares investment costs. The more comprehensive the BITE design is, the lower support costs will be.

Conclusions

During the development of new equipments, the scope of design trade-offs is limited only by the innovativeness of the designers as constrained by the logistics alternatives. These trade-off studies constitute an important part of the LCC function. They must be commenced at the very onset of the conceptual design phase and be continued throughout the design and development of the final hardware.

Quantitative values of LCC can only be approximated during the conceptual design phase due to lack of hardware detail. As concepts and designs mature through an integrated logistics/design process, these approximated values must be refined and tracked to ensure the most effective system.

Cost Summary

The estimated program cost including the nonrecurring costs plus the recurring costs for 30 production systems over a 10-year life cycle are summarized below. Costs are expressed in now-year dollars, assuming that the technology developments discussed in this report are all accomplished. The bases for the estimated costs are described in succeeding sections.

	Total Development Cost	Unit Production Cost[1]	Total Operating Cost[2]	Program Cost[3]
Investment Cost	$40M	$ 7M	–	$ 250M
Yearly Operating Cost	–	–	$45M	$ 45M
Documentation	$ 4M	$20K	–	$ 4.6M
Training[4]	$ 2M	–	–	$ 2M
Total				$ 301.6M
Life Cycle Cost, per system, per year[5]				$1,005.3K

[1] 30 systems, cost per system

[2] 30 systems for 10 years total

[3] 30 systems for 10 years, plus development (sum of development, production, and operating costs)

[4] Instructor's Course at ITT Gilfillan

[5] This is the total program cost, spread over 30 systems for 10 years.

Initial Investment Cost

For purposes of estimating the investment cost of the system, an equipment description was developed which allocated the performance and design of each subsystem down to the lowest functional electronic unit. (For structural and microwave sections, the allocation was generally to the lowest field-replaceable assembly.) Roughly speaking, this unit level corresponds to the level of a line replaceable unit (LRU). Examples of typical LRUs would be: digital circuit boards, memory boards, transmitter modules, receiver low-noise amplifiers, individual low-voltage power supply modules, etc. Subsystem elements that are not functional (such as racks, enclosures, etc.) were considered as cost elements of the subsystem.

The development of nonrecurring and recurring cost estimates were based on a full development program; fabrication of a first production unit; factory test; delivery; IOT&E (Initial Operational Test and Evaluation); and production of 29 additional systems. Thus, the recurring cost is for 30 systems.

The methodology of estimating involves the following steps:

a) For each LRU (or other cost element), a target cost for the recurring cost of the LRU for the first production system was established. (This target cost may be derived from recent actual costs of equivalent or similar units in production; from cost-complexity factors related to IC counts, size, weight, etc.; or from judicious allocations of expected costs of constituent parts.)

b) The linear sum of the target costs for LRUs and other cost elements results in the expected recurring cost for ***one*** system.

c) Standard statistical methods are used to estimate the (lower) ***average*** cost across the total production run (in this case 30 systems).

These steps give an estimate of the ***recurring*** portion of the initial investment cost of the radar.

The ***nonrecurring*** cost has been estimated by use of an internal parametric model, based on an assumed development schedule, subsystem LRU count, and equipment type. The model is based on a selected peak staffing level for each of 12 design groups, with separate inputs for expendable material, travel, computer charges, and other direct costs. These cost inputs (labor, material, and other direct costs) form the basis for the estimate of nonrecurring cost.

Yearly Operating Cost

The yearly operating cost consists of the *incremental expected yearly cost of* operation of the radar, not included in cost elements.

For estimating purposes, the site manning is assumed to be one full-time contractor technical representative, or equivalent-cost military personnel.

The cost model for operating cost also includes the recurring cost of power. For this system, the primary power recurring cost is the fuel cost for the generator, which is rated at eight gallons/hour at full output. An operating schedule of 1,000 hours/year is assumed, and a fuel cost of $1.25/gallon.

Documentation

The estimate for documentation includes the preparation and delivery of the technical manuals required to install, operate, and maintain the equipment; as well as the additional costs for documentation of the nonrecurring management, design, test and validation, including assumed plans, procedures and reports.

Personnel Training

The estimate for maintenance personnel training includes the design of a training course, including lesson plans, training aids, student notebooks, block tests, and class handouts; and the actual conduct of the training course. This estimate assumes an instructor's course, taught at ITT Gilfillan.

Life Cycle Cost

The life cycle cost, per system, per year, represents the average cost per year, per system, for 30 systems over a 10-year period, and *includes* an apportioned amount for investment cost, yearly operating cost, documentation, and training.

(Note: This calculation assumes zero value at the end of 10 years, whereas, in fact military equipment can frequently be extended in service for over 20 years, in a cost-effective manner. The ATR is assumed to be designed for a service life of at least 15 years.)

Section 8

ALTERNATE SYSTEM APPROACHES

8. ALTERNATE SYSTEM APPROACHES

8.1 THIRD PERFORMANCE LEVEL SYSTEM (AZIMUTH MECHANICAL COMMUTATOR SCAN)

Alternate system approaches were considered in addition to the baseline system described in previous sections of this report. The objective of investigating this alternate approach was to define a low cost system with reduced performance capability (third performance level).

The third performance level system configuration and antenna block diagram is presented in Figures A and B and the motivation behind this design was to achieve a compromise between a very low data rate mechanical scanning high inertia antenna, and a high data rate (but potentially costly) electronic beam switching array. By utilizing a relatively low inertia commutator feed for azimuth beam forming and for azimuth beam scanning it becomes possible to provide rapid (relative to a large rotating antenna) mechanical azimuth beam pointing thereby permitting a track-while-scan (TWS) capability. The identifying characteristics of the third performance level system are listed as follows:

- Cylindrical antenna array for full azimuth coverage to 20 degrees elevation
- Six simultaneous or sequential (one pulse repetition period) transmitter beams and six receivers
- Pairs of simultaneous beams are separated 120 degrees in azimuth
- Azimuth scan is basically sequential via mechanical rotating commutators
- Elevation scan can be randomly selected via electronic beam switching
- Sequential target tracking performed via mechanical commutator during search interrupt.

In the commutator approach the six transmitter beams are formed sequentially or simultaneously in one pulse repetition period. For sequential transmission a single beam transmitter pulse is fed to the single-pole six-throw switch, shown in Figure B, which selects the proper commutator input port. The commutator output consists of an array (along the outer circumference of the commutator) covering a 120 degree sector, three sectors are used for each of the two commutators resulting in a total of three azimuth beam positions for each pair of beams (i.e. upper and lower commutators).

The azimuth beams formed by the commutators are fed to vertical beam control units (switching networks) which energize the appropriate input port (for elevation beam pointing) of the beam forming Rotman lenses.

Azimuth amplitude weighting is achieved in the commutator and elevation weighting in the Rotman lenses.

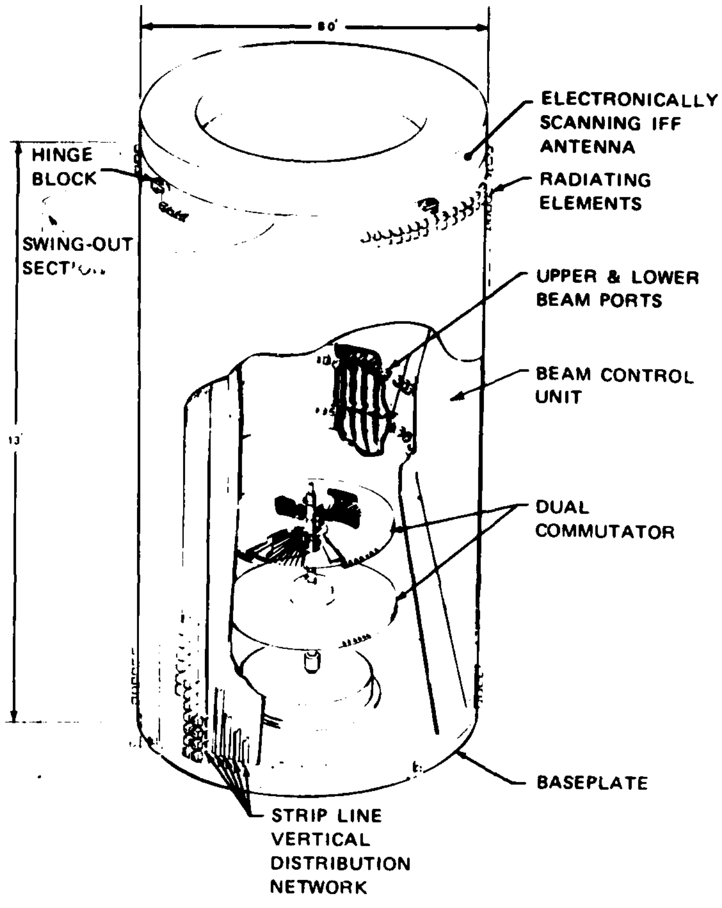


Figure A. Cylindrical array using commentator feed

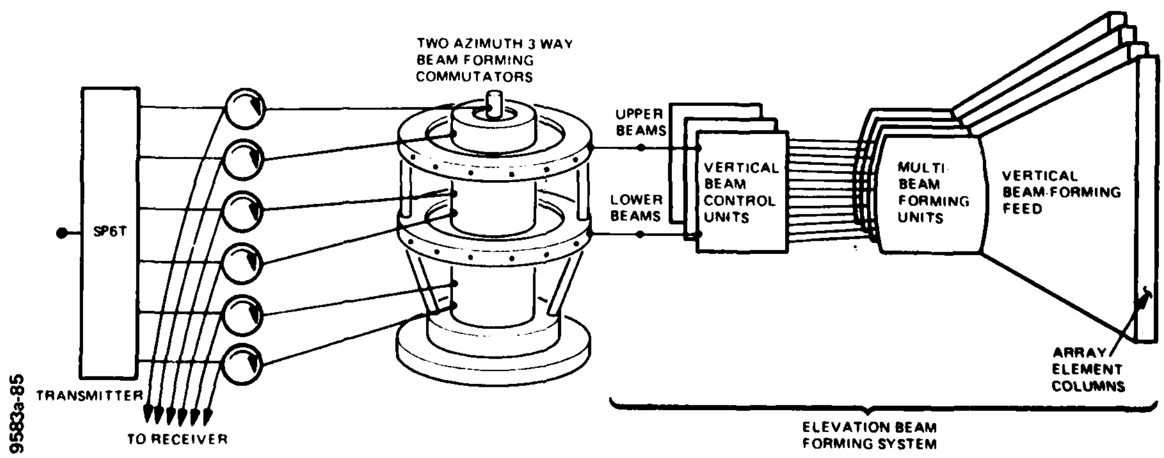


Figure B. Cylindrical array block diagram

A typical pulse sequence and beam pattern is illustrated in Figure C for the sequential transmit pulse mode.

The C-band commutator system approach appeared to have several significant advantages early in the study. The significant advantages that appeared were:

a) Constant azimuth beam width with azimuth pointing angle (i.e., a uniform azimuth effective aperture)

b) 360 degree azimuth coverage with cylindrical array

c) Single vehicle installation for cylindrical antenna.

Later in the study, however, it was learned that vertically oriented Rotman lenses would tend to produce systematic phase errors resulting in poor azimuth sidelobes in the cardinal plane. Azimuth sidelobe performance is vitally important in a stand-off jammer and/or ARM environment.

It was also learned later in the study that the taper and other losses had been optimistically estimated by more than 3 dB. Since the aperture area is near its upper limit from a mobility point of view this loss must be recovered by increased search time, increased power or reduced range. Of these three, reduced range probably is the most attractive.

Higher average powers would not only produce significant temperature rises in the antenna but also require additional prime power. Slower search times would further constrain the already limited track data rate.

The major risk areas associated with the third performance level system are summarized below:

a) May achieve relatively poor sidelobe performance in the azimuth cardinal plane due to systematic phase errors

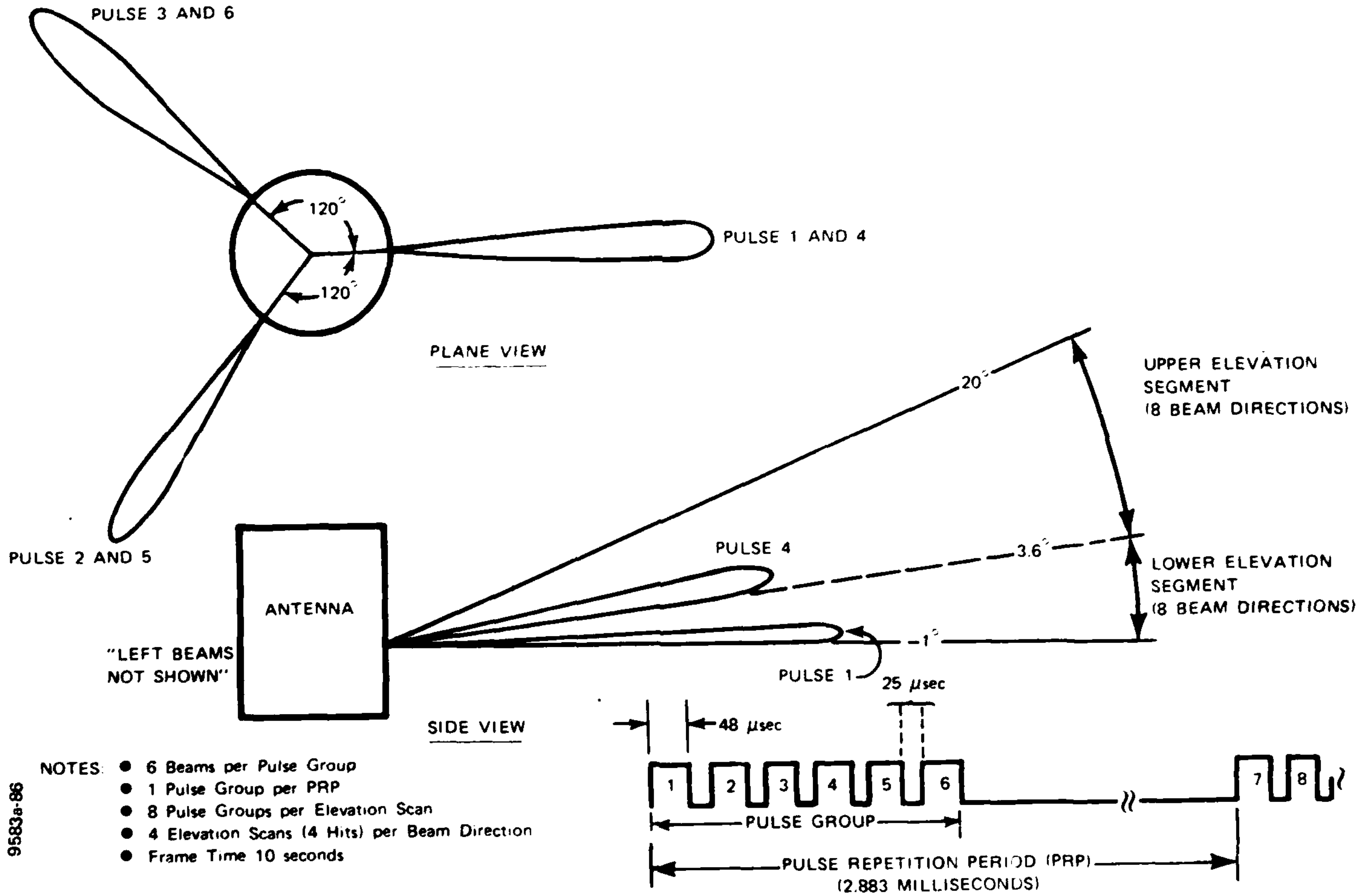
b) Power aperture product will be approximately 3 dB poorer than baseline system approach

c) Number of target tracks ($\approx$25) per 10 seconds is severly limited relative to baseline approach

d) Cannot use distributed solid-state Transmitter (hence losses are increased and reliability is reduced)

e) Rapid beam direction random access is only achieved in elevation.

Of these risk areas the limited track data rate is probably the most critical. Future target densities will very likely necessitate the use of an electronically steerable array.



NOTES:
- 6 Beams per Pulse Group
- 1 Pulse Group per PRP
- 8 Pulse Groups per Elevation Scan
- 4 Elevation Scans (4 Hits) per Beam Direction
- Frame Time 10 seconds

Figure C. C-band tactical antenna beam scan program

The sequential pulse mode has several major difficulties. These are:

- Twenty-five microsecond switching time between pulses uses an appreciable portion of the total transmit time and therefore significantly increases the search time while reducing the available time for tracking
- High-power ultra-fast switches are required for the single-pole six-throw transmitter switch
- Energy management between beams must be achieved on a pulsewidth basis which could complicate pulse coding implementation.

By transmitting the six transmitter pulses simultaneously one can eliminate the above disadvantages. Energy management can be achieved by appropriately sharing the available transmitter power by relatively slow high-power distributors on a pulse period basis.

8.2 FIRST PERFORMANCE LEVEL SYSTEM DISCUSSION (Digital Beam Forming on Receive only)

The first (highest) performance level system is identical to the baseline (mid-performance) system with the exception that receive beams are formed digitally rather than with the elevation Rotman lenses (one for V&H polarization) and associated switching networks.

The first performance level configuration increases the number of required receiver channels and A/D converters by a factor of 138. Processor requirements are also increased. This concept is illustrated in Figure A.

Two potential advantages might be gained over the baseline approach with the digital beam forming configuration. These are:

Multiple receive beams for multisite correlation to passively locate jammer sources

Fine receive beam pointing to null escort jamming sources.

The utility of these advantages are extremely dependent upon the operational usage of the radar relative to the defense system complex. Certainly, passive source location is an extremely desirable characteristic. It is possible that these functions, however, may be more efficiently obtained by specially designed auxiliary equipment. Utilization of the existing radar aperture is on the other hand an attractive possibility which should not be overlooked.

Considerable technological development is required to achieve the first level system design relative to the baseline design. The major area for development is low-cost, high-performance chip receivers which exhibit low-noise figures, high-dynamic range and wide instantaneous bandwidths.

Protective limiters and sensitivity time control (STC) would be implemented at RF prior to the receivers and phase/amplitude tracking or calibration would also be required to maintain excellent sidelobes. It is believed that the receiver digital beam forming approach, although attractive in concept, will be impractical to implement within the time frame under consideration.

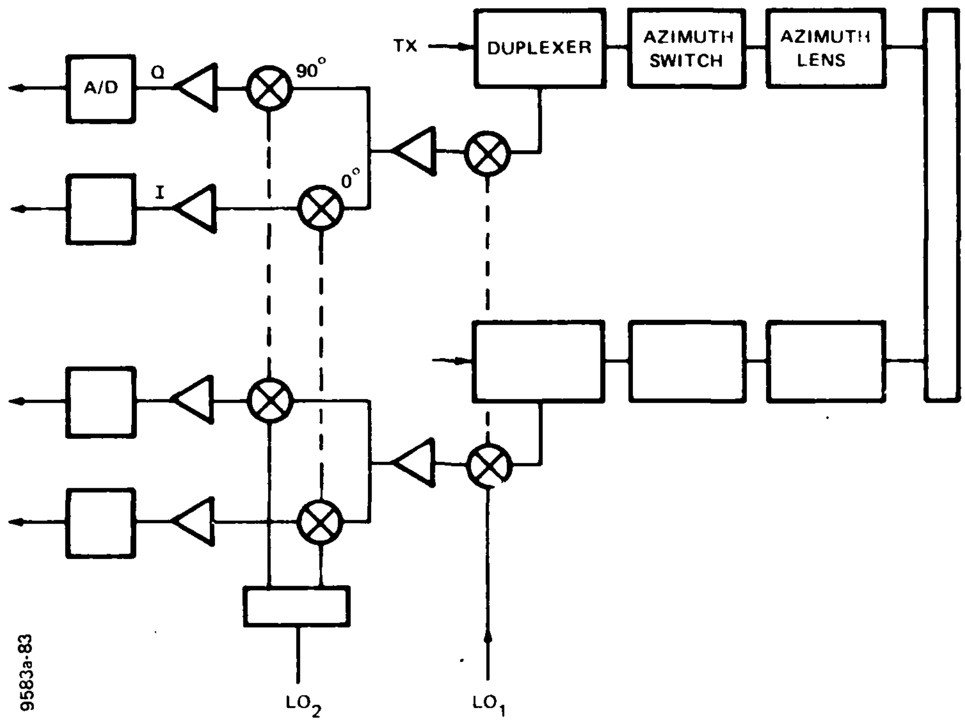


Figure A. Technique for digital beam forming on receive

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